CHAPTER V
ARM-LEG REACH AND WORKSPACE LAYOUT

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This chapter presents information on functional reach measurements relevant to the design and layout of workspaces in the Space Shuttle and Spacelab programs. Most of the existing data described in the following review have been taken under standard gravity conditions on the earth's surface, with specific workspace constraints, i.e., subject usually in a seated position, with fixed backrest and seat surface angles, and lap and upper torso restraint systems that may severely limit the amount of body movement. The measurements were also made on populations anthropometrically selected to be representative of the appropriate user group. In short, the intent was always to gain reach data that would be applicable under a given set of design conditions for one group of people with specifically defined reaches. As a result, functional reach data that are immediately and directly applicable to space vehicles in a zero-g environment, for all practical purposes, do not presently exist.

In the present NASA project we are concerned with potentially very different sorts of workspace conditions, i.e., standing, or "free-floating" in the neutral body position in a state of weightlessness, where there may normally be no restraints on body position or movement. In order to stabilize body position in a zero-g environment, some form of mechanical restraint such as handholds, waist belts, or fixed shoes, must be utilized. Even with restraints, however, there will probably be considerably more body movement possible than that encountered in any one-g reach study to date and greater freedom of body movement implies greater reach distances.

In addition, the potential Space Shuttle-Spacelab population differs anthropometrically from those groups on which functional reach data are currently available. We are no longer dealing with a precisely defined "U.S. Air Force" population, or even with "U.S. drivers," but rather with a potentially worldwide population that varies markedly in body size and reach, from perhaps 5th percentile Oriental females to 95th percentile U.S. or Northwestern European males. In addition, since the space vehicles presently envisioned may be operational through the period 1980-1990, and since secular changes in body size are known to be taking place in many populations, it will be necessary to take into account possible increases in functional reaches during that time period.

In this chapter each of the above variables will be discussed as necessary, and the most appropriate basic reach data will be presented along with recommendations for applying correction factors to adjust for differences in (1) workspace, task, and body position; (2) environmental conditions-primarily g forces; and (3) anthropometric characteristics of various populations.

Review of Existing Data on Functional Reach Measurements

Static Reach Measurements

Traditional measurements of anatomic arm length, such as shoulder-elbow or elbow-fingertip lengths, or of anatomic leg length such as buttock-knee length, have long been included in the battery of dimensions taken in many anthropometric surveys. Such "static" measurements, however, have generally been of relatively little use to those concerned with how far a person can reach and perform some specified task.

In attempting to deal with this problem, some anthropometric surveys have included limited kinds of arm reach measurements, usually two or three dimensions on the outstretched arm. Hertzberg et al. (1954), for example, includes such measurements as "arm reach from wall," a wall-to-fingertip dimension taken with both shoulders against a vertical surface and the arm extended horizontally. Similar reach measurements have also been included in more recent anthropometric surveys (Clauser et al. 1972; White and Churchill, 1971) but ultimately they are of limited utility in equipment or workspace design since they describe a specific reach to a single point immediately in front of, or directly above, the subject. These dimensions tell us nothing of what other reaches might be to almost innumerable other points surrounding the subject, though crude extrapolations can be made in some cases. Nor can static reach measurements accurately describe the effects of body movement. For this purpose, different kinds of reach measurements, specifically "functional" reach measurements, are required.

Functional Reach Measurements

All measurements of functional reach are more difficult to obtain and to present in a meaningful way than are static measurements. The more important factors contributing to this problem are: a) variations in body position including, if seated, seat height above the floor and angulation of seat surface and of backrest; b) the presence or absence of restraint systems for the body; c) anatomical locations of such restraint systems; d) the kind of reach to be made, or the task to be performed; and e) finally and most importantly in the present case, the presence or absence of g forces.

One of the earliest attempts to deal systematically with the measurement of functional arm reach was that of King, Morrow and Vollmer (1947) who measured 139 naval personnel to determine the boundaries of the maximum area for the operation of manual controls. In this study the subjects were seated in a standard pilot's seat with a locked lap belt and shoulder harness and kept their backs against the backrest cushion. A later publication extrapolated the values of these reaches that would be possible with 18 inches of forward shoulder movement permitted (King, 1948). A similar approach was utilized by Emanuel and Dempsey (1955) in an Air Force study of the effects on arm reach of a partial pressure flying suit. Ely, Thomson and Orlansky (1963) developed graphic presentations of functional arm reach which have some utility as very rough guides or indicators of reach, but are lacking specificity and are difficult to apply, especially since the means of determining the data were not specified, nor were the physical characteristics of the population on which they were measured.

Dempster and his associates (Dempster, 1955; Dempster, Gabel and Felts, 1959) have presented an excellent theoretical and methodological approach to the problem of functional reaches and "kinetospheres", but they were not primarily concerned with obtaining reach data on specific populations for specific applications. The data again are of limited practical utility. A somewhat different device and technique for obtaining arm reaches was described by Wright (1964), but also without applicable data.

These earlier data have been largely superseded by the work of Kennedy (1964), who determined the outer boundaries of grasping-reach envelopes for a shirt-sleeved operator by making measurements at a total of 24 vertical planes intersecting with 12 horizontal planes, resulting in 288 measurements for each of 20 subjects.

Stoudt et al. (1970) obtained functional arm reach measurements on 100 subjects, 50 males and 50 females, selected to approximate the general U.S. adult driving population in height and weight. The purpose was to provide data to assist in establishing the outer limits for the location of controls in motor vehicles. One hundred and twenty arm reach points were defined for each subject.

Other studies on functional arm reaches relative to U.S. automotive design, have been conducted for the industry by Woodson et al. (1971), and within the industry by, among others, Chaffee and associates (1968), and by Hammond and Roe (1972) for the Society of Automotive Engineers. In the European automotive industry, arm reach studies have been conducted by, for example, Rebiffe et al. (1969).

The discussion so far has related only to arm reaches. Leg reaches may also be important in workspace layout and design, though perhaps somewhat less so in a space environment. Data on functional leg reaches are unfortunately even more imperfectly known than are arm reach data. Thorough rigorous studies comparable to those made on arm reaches are non-existent. Leg reach has been investigated primarily from the point of view of range of motion at the joints of the leg, and of leg strength exertable at different leg positions and angles, rather than from a concern about spatial limits for operation of foot controls. The single exception is some new, limited, information, as yet unpublished, by Laubach and Alexander (n.d.). Perhaps the single best effort relative to layout of foot controls is that of Ely et al. (1963). However, the lack of specificity of the anthropometric data upon which it was based, and the rather tentative nature of the somewhat overly generalized recommendations, make the study difficult to use except as a very rough guideline.

The major difficulty with all functional reach studies described above, is that they have been conducted under very specific workspace conditions, usually seated with a given restraint system, always in a one-g environment, and on specially defined populations in terms of physical and anthropometric characteristics. In attempting to utilize these data under other conditions such as weightlessness, or for other populations, serious problems of extrapolation arise.

With regard to functional reach studies designed to determine capabilities in a space environment, both the General Electric Space Division (1969), and the Martin Marietta Corporation (Lenda, Rosener, and Stephenson, 1972) have carried out experiments under water, with neutral buoyancy conditions simulating a state of weightlessness. These data have been summarized in Man/System Design Criteria for Manned Orbiting Payload, Section 5. Anthropometry/Crew Capability (National Aeronautics and Space Administration, 1974).

These studies are quite useful in that they indicate for the first time, in a definitive way, how functional reaches differ in a neutral buoyancy environment simulating zero-g conditions. Unfortunately, because of the small numbers of subjects involved and their lack of representativeness of the anthropometric range of the future spacelab populations, the data are of very limited direct applicability in determining functional reach areas and workspace layouts. As the NASA report states, these data "...should be used only as guideline information. The design of a crew station shall assure that all tasks required at the station are located so that all of the user population can perform the task. This means that all tasks must be located well within the reach envelopes shown...so that the tasks can be performed by a 5th percentile woman". (National Aeronautics and Space Administration, 1974). Unfortunately, the phrase "located well within" is so general as to be of little utility in establishing any specific guidelines for the maximum permissible reach distances in the layout of workspaces.

The best, though far from fully satisfactory, solution to this dilemma, is to select those reach studies made under one-g conditions that appear to be most useful for NASA purposes, and to present those data (with all their limitations) with accompanying extrapolation factors for different environmental conditions, specifically utilizing and integrating those data and information available on zero-g, or simulated zero-g, reaches. Selected arm reach data and instructions for extrapolation appear in the last two sections of this chapter.

Comparability of Data from Reach Studies

Each functional arm reach study has utilized a different population for its subjects. The earliest, and some of the most rigorous studies, were made on military pilots, (e.g., King et al., 1947; Kennedy, 1964) and hence represent the arm reaches of a rather highly selected, exclusively male, fairly young, anthropometrically relatively large, and healthy, United States population. More recently, comparable data have become available on a United States female population (Kennedy, 1976).

Later studies have dealt with the United States general civilian driving population and, as such, included both males and females over a fairly wide age range (Stoudt et al., 1970; Chaffee, 1968; Hammond and Roe, 1972).

Functional arm reach studies on non-United States populations are considerably more limited. One of the few available was done by Bullock (1974) on Australian pilots, both male and female. Subjects were selected on the basis of height and weight to be anthropometrically representative of the parent population. Comparable kinds of functional arm reach data on non-European/American populations are not generally available.

Where data are not available, extrapolation from the measured to the unmeasured (for functional reach) groups becomes necessary. Fortunately, functional arm reaches are closely related to overall body size. Fairly good indications of the reach of different ethnic or national populations can therefore be achieved by selecting certain percentiles of United States data to be the equivalent of different percentiles of other populations. For example, the 5th percentile reach on a United States population may be the equivalent of the 10th or 20th percentile reach on another, anthropometrically smaller, national or ethnic population. While this does present some problems and potential pitfalls in the interpolation process, they are relatively small as compared to the difficulties inherent in extrapolating from one set of workspace measuring conditions to another.

A second source of variance between studies is difference in measuring techniques. Functional reach data have been obtained by a variety of means and through use of different basic reference points from which the reach measurements are indexed. Regardless of which basic reference points, measuring systems, or techniques of recording the dimensions are used, the data are employed to serve a common purpose, namely to define the outer boundaries of a workspace to which the subjects can reach, given the specific conditions under which the measurements were taken. The problem is not primarily one of lack of comparability of measuring systems or techniques; if the measurements are taken properly, regardless of which system is used for a given set of conditions, the results should be generally comparable. The major source of difficulty arises when the conditions under which the measurements are taken, vary. The most important of these conditions is probably body position, i.e., standing or seated; if seated, backrest angle, type of restraint system, etc. The major challenge is to find the best way of extrapolating, or converting, functional arm reach measurements taken under one set of conditions, to measurements that will, as accurately as possible, describe the functional reaches under a different set of physical workspace conditions.

Data Presentation

Percentiles are the single most effective way of presenting anthropometric data, including functional reaches, for purposes of workspace design and layout--provided they are properly understood and utilized.

Obviously, the 50th percentile (which usually approximates the average), in functional reach, means that one half of the subjects in a given population have reaches shorter than that value, and one half have longer reaches. In similar manner, the value of the 95th percentile reach is usually that of a fairly large, or long-armed person; only 5% of all the people in that population have longer arm reaches. However, what is generally more important for establishing workspace layouts and central locations are the values of the lower percentiles, i.e., the people in the population with the shortest reaches. For example, 5th percentile reaches are sometimes given as the values for establishing the lower limits of reach; 95% of the population can reach beyond the 5th percentile; only 5% of all the people in that population have shorter arm reaches.

The practical problem here is that if it concerns the locations of a presumably important item, then it may be totally unacceptable for fully 5% (or one out of 20) of the population to be unable to attain that reach. This might well be true in a spacecraft. From this point of view, the 1st percentile value of reach would be better--only 1 percent could not reach this far. Ideally, if everyone must be able to achieve a given reach, then the smallest reach in the entire population must be used--this would necessitate the use of the minimum, or single smallest reach value. In practice, this may not be always necessary, since most reach values usually contain a built in "safety factor." That is, under normal conditions, a 5th percentile reach might be achievable by someone of the 4th, 3rd, 2nd or perhaps even 1st percentiles of "normal" reaches with extra effort or body repositioning. Similarly a 1st percentile reach might well be attained by all of the smaller percent of the population if there were no really aberrantly small members of the group as presumably there would not be in a spacecraft population.

Workspace Design as Based on Functional Reach Measurements

As noted above, a prime requirement in the layout of any workspace is that all controls or tasks that are in any way related to manual or pedal operation, be located so that they can be reached and operated or performed satisfactorily by all members of that workspace population. To achieve this, measurements are needed that define just how far given percentages of that population can reach under the conditions anticipated for that workspace. This can be most effectively accomplished by selecting a representative (both anthropometrically, and for other variables related to reach) sample, determining their functional arm reaches, and defining an overall, three-dimensional "reach envelope" that specifies both the maximum permissible outer limits, and sometimes optimum location, for the placement of all relevant items or tasks within the workspace.

This ideal procedure has not always been carried out in practice. Sometimes interpolations and extrapolations must be made from existing data, and sometimes reach locations and outer limits must be established on the basis of "guestimate", perhaps supported by brief trials involving only a few subjects. This may be relatively easy to do and can be an acceptable procedure where the reach locations in the area surrounding the operator are limited in number and complexity, and can be checked rather easily for adequacy. However, potential difficulties may arise where a number of controls or tasks must be located within a given area, and all clearly cannot be placed in the area immediately surrounding the operator where they can be easily reached. When some items must be located in less appropriate areas on the outer periphery of the workspace, it becomes essential to know exactly where the outer boundaries are for the accommodation of all persons in the population.

A considerable amount of information relative to the layout of workspaces in terms of functional reach is available, though of variable quality, and variable relevancy to the present concerns of zero-g conditions in Space Shuttle-Spacelab. It should be noted that these are not only studies of functional reach per se (i.e., King et al., 1947; Kennedy, 1964; Stoudt et al., 1970) but also are studies that make recommendations for workspace layout and design dimensions to accommodate the functional anthropometric capabilities, whether known or assumed, of the intended occupants or operators.

General guidelines for the layout to workspaces can be found in the first edition of the Human Engineering Guide to Equipment Design (Ely, Thomson, and Orlansky, 1963; Damon, Stoudt, and McFarland, 1963), as well as in Damon, Stoudt, and McFarland (1966), Van Cott and Kinkade (1972), McCormick (1970), and Roebuck, Kroemer and Thomson (1975). Though these studies (with the exception of the latter) do not present specific design recommendations directly applicable to the zero-g condition--nor was this their intent--they are all useful in terms of background, methodology, and approach.

The first aerospace study dealing with anthropometric data and aircraft design was carried out during World War II by Randall et al. (1946). The study included, in addition to body dimensions of Army Air Force pilots, certain aspects of cockpit design and spatial accommodation in fighter and bomber aircraft. Arm reach measurements were limited, as were related design specifications. More recently, design specifications for military aircraft relative to control location can be found in the human engineering section of a U.S. Air Force Systems Command Manual (1972). The reach-related dimensions treated here concern spatial location and travel of throttle handles, and foot pedal location and adjustments, all relative to a neutral seat reference point.

A more detailed study for control location based on arm reach is that of Garrett, Alexander and Matthews (1970) which defined reach envelopes for the outer boundaries of controls in a series of positions with different conditions of clothing and equipment, and body restraints. For each position and condition, a design dimension was specified as follows, e.g.,: "to manipulate with the right hand a rotary knob located 60° to the right of center and 18" above the deck the knob must be placed no further than 30" from the Seat Reference Point". All such data were taken in the seated position, under one g, and with a degree of specificity regarding workspace conditions that makes extrapolation to the zero-g, Space Shuttle environment extremely difficult.

In spacecraft, on the basis of astronaut zero-g Skylab experience, some specific dimensions relative to workspace layout and dimensions have been made. These concern the optimum work surface height and change in eye position, both relative to foot restraint position, and, most importantly, changes in functional reach.

Certain general design features of the Space Shuttle and Spacelab relative to functional reach considerations appear to be fairly well established. For example, the Space Shuttle is designed to carry a crew of seven, including pilot, co-pilot, mission specialist, and other scientific or technical personnel. The primary flight stations are organized in the usual pilot-co-pilot relationship, with other personnel to the rear. The g forces involved here in launch and re-entry will require traditional seated positions, probably with lap and torso restraints, a factor which must be considered in control layouts for these locations.

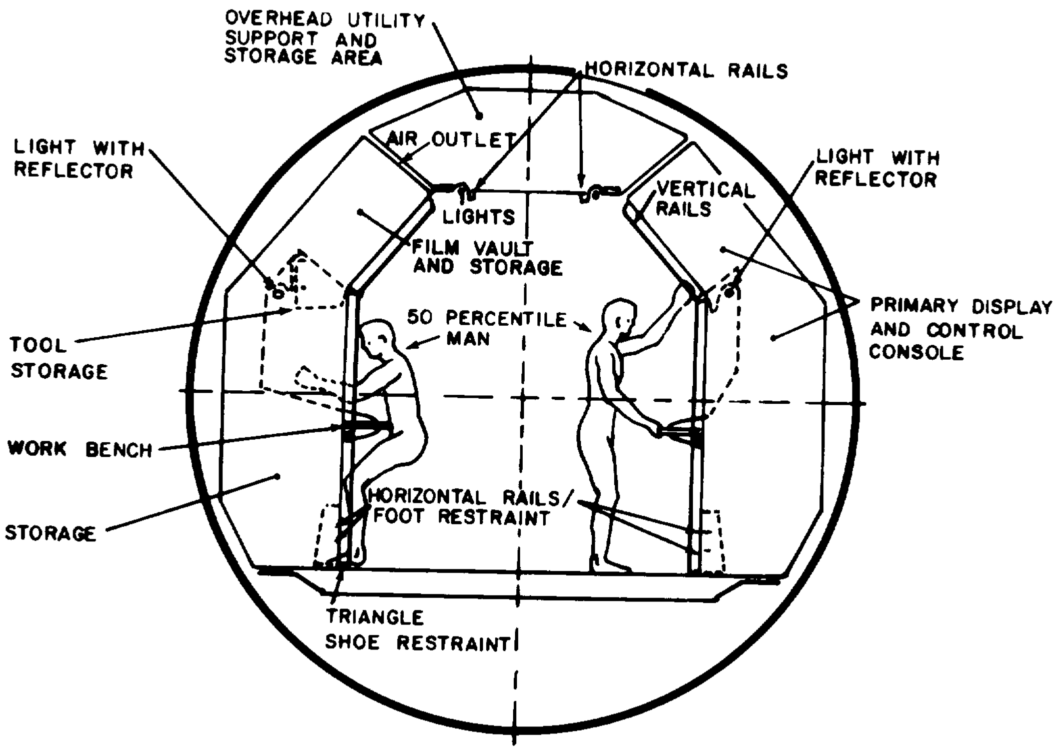
The Space Shuttle will also provide accommodations for all crew members including food, waste management, sleeping and personal hygiene. For these functions zero-g conditions will apply, as they will for all Spacelab operations. Preliminary indications are that the basic Spacelab design will be similar to that shown in Figure 1. Some form of foot restraint will be used in Spacelab for body stabilization, which will considerably increase the potential range of different body positions from which arm reaches can be made, as suggested in Figure 2.

These features and other factors affecting functional reach capability are outlined and described below.

Biological Factors Affecting Functional Reaches

A wide variety of different factors influence the distances that people can reach. Many of these are related to the innate characteristics of the individual, such as age, sex, race, health status, physical condition, etc. These biological variables are, for the most part, either unalterable or relatively difficult to alter. Selection of individuals in terms of the specific biological characteristics related to given kinds of functional reach is, generally speaking, the only way in which such variables can be "controlled". The effects of the more important biological variables

TOP: Core module cross section showing workbench and console station.
BOTTOM: Typical internal rack arrangement.



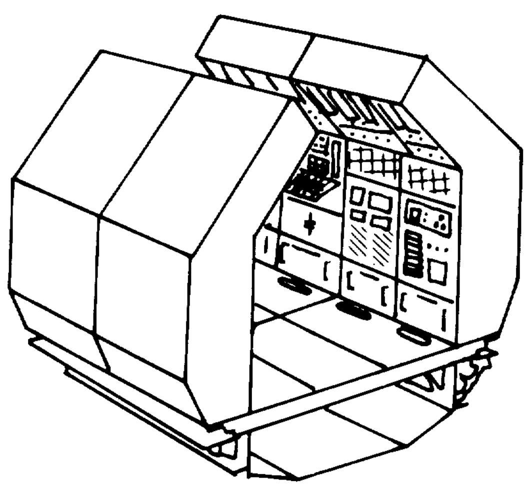


Figure 1. Spacelab workspaces (from Thompson, 1975).

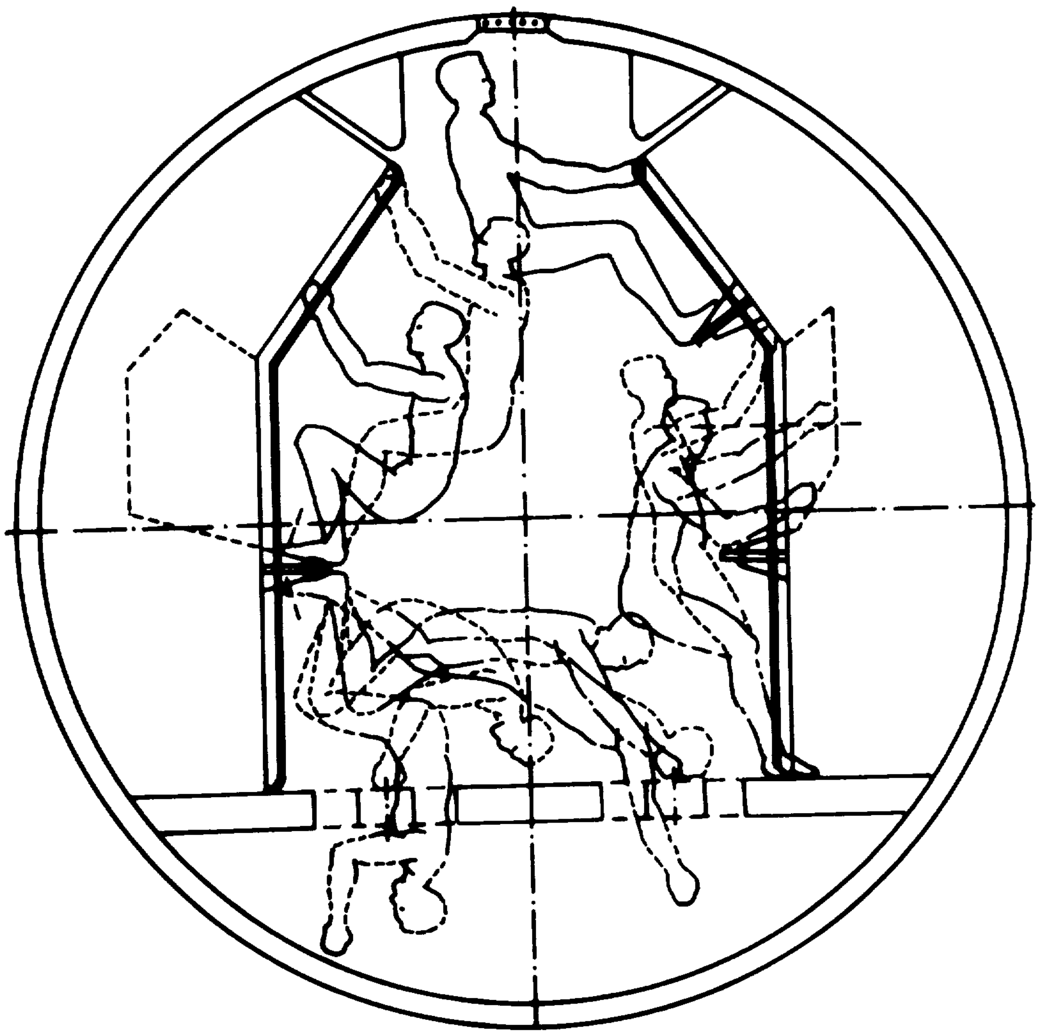


Figure 2. Portable foot restraint positions (from Thompson, 1975).

related to functional reach in the projected Space Shuttle-Spacelab environment are summarized below. A discussion of environmental variables follows in the next section.

Age

Functional reach is closely related to overall body size. For all practical purposes, full growth and maximum body size (except for weight-related dimensions) are achieved by about age 20 in males and about 17 in females. Since the Spacelab population will be all adult, this aspect of the aging process should not be a factor in the functional reaches of this group, although there may be slightly reduced body sizes in middle-aged and older groups, and, in addition, some reduction in functional reaches may occur because of certain degenerative or arthritic type conditions which are more prevalent with increasing age.

Sex

Differences in overall body size, and therefore in functional reach, are both marked and significant between the sexes. For example, men, on the average, are roughly five and a half inches (14 cm.) taller than women, and about 30 pounds (13.6 kg.) heavier. In static forward arm reach, perhaps more accurately described as arm length, women's average values are three inches (7.6 cm.) less than those for men.

Such sex differences also apply to functional reaches, and it is therefore necessary to take the sex distribution of a group into account in designing and laying out workspaces. Any workspace designed around, and adequate for, a given male population may well be inadequate for some percentage, perhaps substantial, of a female population.

Race-Ethnicity

There is a fairly wide range in overall body size, and therefore in associated reach dimensions, among the various races, ethnic and national groups of the world. U.S. and Northwest European populations tend to have the largest body sizes, with Southern and Southeastern Europeans somewhat smaller, and Orientals or Asiastics generally, though not always, smaller still. (See Chapter II, Human Body Size Variability, for detailed comparative data.)

Secular changes in body size, i.e., an evolutionary trend towards larger body size over time may account for relatively small differences between these groups, since they were measured at different times over the past 20 years. However, by far the larger part of the differences is due to the innate biological variability in body size between racial, national, ethnic, and socio-economic, groups. For present purposes, the extremes of such variability in body size, and therefore in functional arm reach, to be considered are U.S. (male) populations at the upper, or larger, end, and Asiatics (female) at the lower, or smaller, end.

Health-Physical Condition

Since it is reasonable to assume that all persons involved in the Space Shuttle-Spacelab program will be considerably above average in health status and that they will also be at least average or above, for their age, in physical condition, the changes in static and functional body dimensions that could result from these variables should not be relevant here.

Secular Trends

There appears to be a tendency towards an evolutionary increase in body size over time. People have been "getting taller". Projections from the Aerospace Medical Research Laboratory (n.d) show, for example, that a U.S. Air Force male population comparable to the 1967 measured population would be expected to be 0.65 inches taller in 1980. Detailed data on secular growth trends to date and indications that such "growth" may have slowed down for at least one population, can be found in Chapter II.

Environmental Factors Affecting Functional Reaches

The other, and equally important, class of variables related to functional reaches are those of an environmental nature. These are usually concerned with the physical characteristics and constraints of the workspace itself, or with the type of task that is to be carried out within that workspace. Present examples of the former are the effects of a zero-g environment, workspace layout and design including body restraints, body position in the workspace, and clothing and equipment. While the effects of weightlessness cannot be changed, most other characteristics of the environment, workspace and task lend themselves to at least some modification.

Gravity

All definitive studies of both static anthropometry and functional reach have been made on the earth's surface under conditions of standard gravity. However, a zero-g environment will affect both static anthropometry and, to a considerably greater extent, functional reach measurements. As has been noted in previous chapters, for static dimensions intervertebral spinal pressures will decrease, resulting in an apparent increase in erect and seated body heights. Such changes, plus a concomitant body fluid redistribution will tend to shift the center of mass of the whole body headward. Since the pull of gravity on the arms will be eliminated, the shoulders will tend to move upward, and the elbows upward and akimbo (Roebuck et al. 1975).

Functional reach dimensions will increase even more markedly under such conditions. This will result in an increase in usable working space and increased reach areas--if the operator is either unrestrained, or only partially restrained, in regard to body movement (Parker and West, 1973). The basic question is, how much will functional reaches increase in a state of weightlessness? A precise answer is difficult because of the many variables affecting functional reach under these conditions, including not only body restraints, but working position, clothing and equipment worn, and type of task to be performed. These factors are discussed below.

Information on zero-g reaches, or on conditions affecting these reaches have been obtained by: (1) observations of films of astronauts' experiences in zero g, (2) astronauts' reports of their own zero-g experiences, and (3) by measurements of simulated zero-g reaches. The latter studies have been made with very small numbers of subjects (five or less) and the results therefore cannot give a clear picture of the range of reaches attainable by any specific, anthropometrically defined, population. However, both sorts of data do give some clear indications of the kinds of differences in functional reach that can be expected under zero g. For example, "downward" reaches are more difficult; there is no gravity assist. Similarly, "upward" reaches will seem easier. Reaches to the rear of the body, with the body anchored at the feet by a shoe restraint, exceeds reach to the front. In a zero-g environment, ankle extension, knee flexion and vertebral extension are more effective, in terms of maximum reach, than the opposite joint movements in the forward direction (General Electric Space Division, 1969). Again, a major factor in zero-g reaches is the fact that it is totally unnecessary, or even desirable, to "sit" at a work location.

Finally, it should be remembered that, while zero-g conditions may be the constant mode for Spacelab operations, for the Space Shuttle there will be forces up to 3-g during launch, and up to 1.5-g during a typical re-entry (National Aeronautics and Space Administration, 1975 b). Consequently, any controls or workspace items that must be reached and operated during these times cannot be positioned on the basis of the greater reach capabilities possible under zero g.

Working Positions

The normal working position of the body in a zero-g environment differs substantially from that in a one-g environment. The seated position is for all practical purposes eliminated, since the sitting posture is not a natural one under these conditions (Johnson, 1975). Seats, with lap belts or other restraints to anchor the occupants are both unnecessary, uncomfortable, and undesirable.

The "standing" position of the body in a state of weightlessness has been found to gradually change from initial erectness, with a straightened spine, to a forwardly bent, semi-erect position. This has been called the neutral body position of weightlessness, and has been defined as that position which the body tends to naturally assume when completely relaxed and acted upon by no external forces. It is a semi-crouched, neither sitting nor standing posture as shown in Chapter IV, Figure 8. It will also be noted that the normal one-g line of sight is depressed about 10^{o} below the horizontal. Under zero-g conditions, because of the natural tendency of the head and neck to incline downward, there is an additional depression of the line of sight, of about 15^{o} (Jackson, Bond, and Gundersen, 1975).

The neutral body position then, is the basic posture that should be used in establishing workspace layout and design. Unfortunately, no adequate body of functional reach measurements exists which have been measured from the neutral body position. Extrapolation from one-g studies, usually in the seated, restrainted position, will be necessary.

Body Restraints

While the absence of g forces will usually facilitate rather than restrict body movement, orientation, or positioning, this same lack of gravitational stabilization will leave the individual without any contrathrust platform. Thus some sort of artificial body restraint system will be necessary to provide an energy sink, or device or place for disposing of energy (General Electric Space Division, 1969).

To accomplish this, three basic types of body restraint or stabilizing devices have been tested either under neutral buoyancy conditions on earth, and/or actual zero-g conditions in space. These are handhold, waist, and foot restraints (See Figure 3). In the former, the individual is stabilized by holding on to a handgrip with one hand and performing the reach or task with the other. This restraint affords a fairly wide range of functional reaches, but body control is difficult, and body stability is poor. In addition, the use of the handhold restraint has been found to be quite fatiguing. For this reason, it is not recommended for any work station that is to be used for any extended period of time.

A waist restraint (for example a belt around the waist in either the seated, erect, or neutral body position) affords good body control and stabilization, but seriously limits the range of motion and reach distances attainable. It could therefore be used for workspaces in which only fairly restricted arm reaches are necessary, but would not be appropriate where longer reaches or frequent body movement, or repositioning, is required.

The third basic system restrains the individual by the feet, either through "Dutch Shoes", a toe-rail, a cleated shoe which interlocks with a "floor" grid, or by suction cups attached to the sole and heel. Shoe restraints, generally, have been found to be definitely superior with regard to range of motion, body control, and lack of fatigue. In neutral buoyancy tests, the shoe restraints were judged to be excellent in "performance,

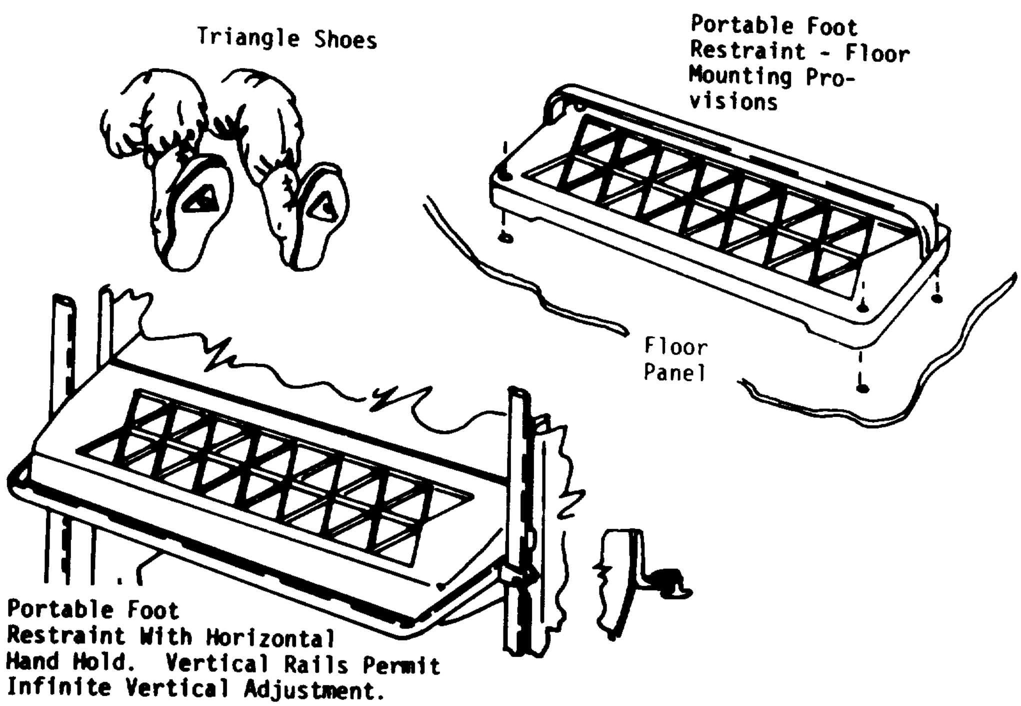


Figure 3. Foot restraint system (from Thompson, 1975).

stability, and deliberateness...as evidenced by the subjects' ability to draw continuous and steady curves". (General Electric Space Division, 1969).

Clothing and Personal Equipment

Clothing and personal equipment worn on the body can influence functional reach measurements. The effect is most commonly a decrease in reach which can sometimes be considerable if the clothing or equipment is especially bulky or cumbersome. Most data on functional reaches have been gathered under so-called "shirt-sleeve" conditions, (light indoor clothing) which do not appreciably affect the measurements. Exceptions are a study by Garrett et al. (1970) who presented data on the functional reach capabilities of military aircrew wearing light weight coveralls (longest reaches), and full pressure suits, both uninflated, and inflated (shortest reaches). In addition, Laubach and Alexander (1975) measured functional reaches on a group of Air Force pilots, first shirt-sleeved with inertia reel unlocked, and then wearing complete winter flying assembly with inertia reel locked. Differences were substantial. Under the very worst conditions for example, it was found that 5th percentile reaches with flying clothing and inertia reel may only be about 60% of shirt-sleeve reaches. More commonly the difference ranges between 70% and 90%, clearly a very significant and practical difference.

If space suits were required during any phase of the Space Shuttle-Spacelab intravehicular operations, this would probably necessitate a substantial reduction in any design reach dimensions established for shirt-sleeve operations. The extent of these differences would have to be determined from "with-and-without" studies using the specific space suits and gear to be employed in that mission. For example, in the underwater, neutral buoyancy tests of functional reach (General Electric Space Division, 1969), measurements were made with the NASA Gemini Spacesuit, but the experimenters noted that direct "interpolation of the values for pressure-suit access volumes is inappropriate unless suits with the same dynamic characteristics are utilized."

For extravehicular activity, the problem of functional reach dimensions would presumably be of relatively little consequence because of body mobility. And, since normal intravehicular activity and operations for both Space Shuttle and Spacelab are planned for pressurized non space-suited conditions (Anonymous, 1975), it should be possible to utilize shirt-sleeved functional reach dimensions for design purposes in these vehicles. There are, it is true, some differences between clothing worn in aerospacecraft in zero g and one g. Zero-g clothing has more and larger pockets--to temporarily store and carry small articles. This should not affect functional arm reach to any appreciable extent. Special restraint shoes, oxygen pack and mask, and communications equipment might be worn (National Aeronautics and Space Administration, 1974), but again, these should not substantially affect functional arm reach (though the suction cup shoe restraint would likely add one to two inches to stature). Special areas requiring the use of space suits, or emergency conditions may, of course, necessitate other provisions.

Task to Be Performed

The length of a functional arm reach is clearly dependent upon the kind of task or operation to be performed by that reach. For example, tasks requiring only finger-tip pressure on a push button could be located at or near the outer limits of arm reach as defined by the finger tip. This would be, essentially, absolute maximum attainable functional reach. However, another task may require rotation of a control knob between thumb and forefinger; this would result in a reduction of the above maximum attainable functional reach of about 2.5 inches (6.4 cm.). Full hand grasp of a control level would reduce maximum reach even more, perhaps by 5 inches (12.7 cm.). Where two-handed operation, or greater precision, or continuous operation, are required, the task must be located still closer to the operator, and maximum functional reach will decrease accordingly.

It should be noted that the maximum reaches referred to above, are those made to the outer limits of the workspace. They represent the farthest distance at which a control or task can be located if necessary and still be operated or performed by the person(s) with the smallest functional reaches in the group. These are not necessarily the optimum locations for such placements, which may well be closer in to the body.

These considerations apply equally well in zero g as to one g, though some minor differences in reach and performance have been reported. For example, any "downward" reach or reach involving bending at the waist will be judged more difficult (though only slightly so) in zero g because of the absence of gravity assist in "pulling" the arm or body down. "Upward" reaches would similarly be judged easier. The general concensus of astronaut Skylab experience was that most manual tasks were performed as easily, or more easily, in a zero-g environment (when foot restraints were used) because of the greater flexibility in body positioning, and the increased efficiency in handling large masses (National Aeronautics and Space Administration, 1975c).

The Data: Functional Reach Measurements

Considerations in Data Selection

There is no single study, or body of data, or functional reach measurement that is immediately and directly applicable to the design of workspaces for the specific environmental conditions and populations anticipated for Space Shuttle and Spacelab through the year 1990. As noted in the discussions above, functional reach studies are always made under a certain set of prescribed conditions for a given population. The intent is to obtain data that can be used in the design of one specific kind of workspace, under conditions and with populations similar to those for which the reach data were obtained.

After review of all available functional arm reach studies that might be applicable to the present design situation, the single most appropriate set of data was determined to be that of Kennedy for both men (1964) and women (1976). Reasons for the selection of these data are as follows: (1) the experimental design, measuring apparatus, and data analysis and presentation were as carefully planned and well controlled as those of any other functional reach study and better than most; (2) they are the only studies which present separate, but comparable, data for both male and female populations; (3) while the number of subjects, 20 for males and 30 for females, is fairly small, they were specially selected anthropometrically to accurately represent the size range of the parent populations. Certain disadvantages of the Kennedy study for present purposes, i.e., seated position with specific seat back and seat pan angles, shoulder restraints, etc., are considerable, but are common to almost all other functional reach studies that might have been selected except for the underwater neutral buoyancy tests. Although the latter were intended to simulate zero-g conditions, the subject population was too small and too anthropometrically atypical to be of any real utility here.

Arm Reach Data - Males

The Kennedy data were obtained on 20 subjects selected to be anthropometrically representative of the U.S. Air Force population. Their dimensions, and those of the female subjects, are presented in Table 1. All functional reach measurements were taken with the subject on a hard, unyielding seat with a backrest angle of 103°, and a seat angle of 6°. The reach task was to grasp with the right hand a small knob between the thumb and forefinger and push away until the arm was fully extended, with the shoulders still in contact with the seat back. Subjects wore light indoor clothing that did not appreciably restrict their reach.

The measurements of reach was as follows. Reaches were made to a series of vertical planes emanating from the seat reference point (intersection of planes of seat and backrest surfaces in seat midline), starting at 0°, or straight ahead, and at 15° increments to the right and left to 180°, or directly to the rear. At each of these angles, reaches were made to a series of horizontal planes, at 5 inch (12.7 cm.) intervals, starting at the seat reference point to 45 inches (114.3 cm.) above this point. All reach dimensions presented in the following tables describe the horizontal distance between the two points defined by (1) the position of a knob being grasped by the thumb and forefinger, and (2) the seat reference vertical, (SRV), or vertical line through the seat reference point (SRP). See Figures 4-13 accompanying the tabular data for further clarification.

In the following tables the "minimum" value column presents the single shortest reach made in the sample of 20 subjects. It is very roughly equivalent to a 1st percentile value, but since it is based on only one individual, the values may be somewhat variable. The 5th percentile value is that of the individual who had the next to shortest reach (or 19th of the 20 in rank). The 50th percentile is the arithmetic mean of the 10th and 11th values, and the 95th percentile is that of the individual with the second longest reach.

Arm Reach Data - Females

These data were obtained on 30 subjects selected to be anthropometrically representative of the U.S. Air Force female population. The subjects' dimensions are presented in Table 1. Conditions of measurement for the functional reaches were comparable in equipment and technique to those for the male subjects, i.e., taken with the subject on a hard, unyielding seat with a backrest angle of 103°, and a seat angle of 6°. The reach task and the unrestrictive nature of the clothing worn by the female subjects were also the same as the men's. Reaches were made for a series of vertical planes emanating from the seat reference point, starting at 0°, or straight ahead, and at 15° increments to the right and left to 180°, or directly to the rear. At each of these angles, reaches were made to a series of horizontal planes at 6 inch (15.2 cm.) intervals starting at the seat reference point to 42 inches (106.7 cm.) above the point. In this latter regard the women's study varied slightly from the men's in which reaches were measured at 5 inch (12.7 cm.) intervals and extended to 45 inches (114.3 cm.) above SRP. Recording of "minimum" values was omitted in the women's study.

Conversion Technique for Different Workspace Conditions

As noted, the above data on functional arm reach for males and females were taken under standardized conditions, i.e., seated position, hard seat, 103° backrest, 9° seat angle, shoulders in contact with backrest during reach, and a one-g environment. These data can therefore be expected to apply directly only to seated workspaces with similar configurations.

Gravity Conditions - Body Movement Restrained

For the Space Shuttle (as opposed to Spacelab) design, the seated position for flight crew, mission specialist, and other scientific or technical personnel during the g forces of launch and re-entry, will be the workspace conditions to which the present data are most directly applicable. If seat configurations are generally similar to those of the simulated U.S. Air Force pilots' seat used in determining the present arm reach data (Tables 2-19), then the latter may be used directly in establishing the layout of these workspaces and control locations--subject only to possible adjustment because of different sized operator groups which is discussed in the next section on conversion techniques for different populations.

TABLE 1
ANTHROPOMETRIC DIMENSIONS OF THE MALE AND FEMALE SUBJECTS UTILIZED IN THE FUNCTIONAL ARM REACH STUDIES*

Dimension (inches)	Males (N=20)		Females (N=30)	
	Mean	S.D.	Mean	S.D.
Age (years)	(27.9)	(5. 1)	(20.8)	(4.03)
Stature	176.8 (69.6)	6.7 (2.63)	162.8 (64.1)	5.74 (2.26)
Weight	75.2 (165.8)	9.35 (20.62)	56.37(124.3)	5.56 (12.26)
Sitting height	92.2 (36.3)	3.45 (1.36)	86.4 (34.0)	2.64 (1.04)
Eye height, sitting	-	-	73.7 (29.0)	2.64 (1.04)
Acromion height, sitting	61.5 (24.2)	3.05 (1.20)	55.6 (21.9)	2.51 (0.99)
Functional reach	81.3 (32.0)	3.86 (1.52)	71.9 (28.3)	3.53 (1.39)
Arm reach from wall	86.9 (34.2)	3.63 (1.43)	-	-
Maximum reach from wall	97.0 (38.2)	3.91 (1.54)	-	-
Shoulder-elbow length	36.6 (14.4)	1.57 (0.62)	32.5 (12.8)	1.68 (0.66)
Forearm-hand length	48.3 (19.0)	1.88 (0.74)	42.4 (16.7)	1.98 (0.78)
Hand length	19.3 (7.6)	0.58 (0.23)	-	-
Buttock-knee length	-	-	57.4 (22.6)	2.16 (0.85)
Biacromial breadth	39.9 (15.7)	1.91 (0.75)	36.3 (14.3)	1.55 (0.61)
Shoulder breadth	-	-	41.9 (16.5)	1.98 (0.78)

*Anthropometric data from Kennedy, 1964, 1976. For definitions of measurements see Kennedy, 1964, Hertzberg et al., 1954, or Damon et al., 1966. Data given in centimeters and kilograms with inches and pounds in parentheses.

TABULATED ARM REACH DATA:

MEN AND WOMEN

TABLE 2

MEN'S RIGHT HAND GRASPING REACH TO A PLANE THROUGH THE SEAT REFERENCE POINT. HORIZONTAL DISTANCE FROM THE SRV*
See Figure 4

Angle to Left or Right	Minimum		Percentiles 5		50		95	
L 165								
L 150								
L 135								
L 120								
L 105								
L 90								
L 75								
L 60								
L 45								
L 30								
L 15								
0								
R 15								
R 30			44.5	(17.5)	52.6	(20.7)	63.5	(25.0)
R 45	41.1	(16.2)	49.5	(19.5)	55.1	(21.7)	66.0	(26.0)
R. 60	44.5	(17.5)	52.1	(20.5)	56.4	(22.2)	66.5	(26.2)
R 75	43.7	(17.2)	50.8	(20.0)	56.4	(22.2)	66.0	(26.0)
R 90	43.2	(17.0)	49.5	(19.5)	56.4	(22.2)	64.8	(25.5)
R 105	41.1	(16.2)	47.5	(18.7)	55.9	(22.0)	64.0	(25.2)
R 120	38.1	(15.0)	46.2	(18.2)	52.6	(20.7)	62.2	(24.5)
R 135	33.0	(13.0)	41.9	(16.5)	48.3	(19.0)	59.7	(23.5)
R 150			35.6	(14.0)	41.9	(16.5)	51.3	(20.2)
R 165					33.0	(13.0)	43.2	(17.0)
180								

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

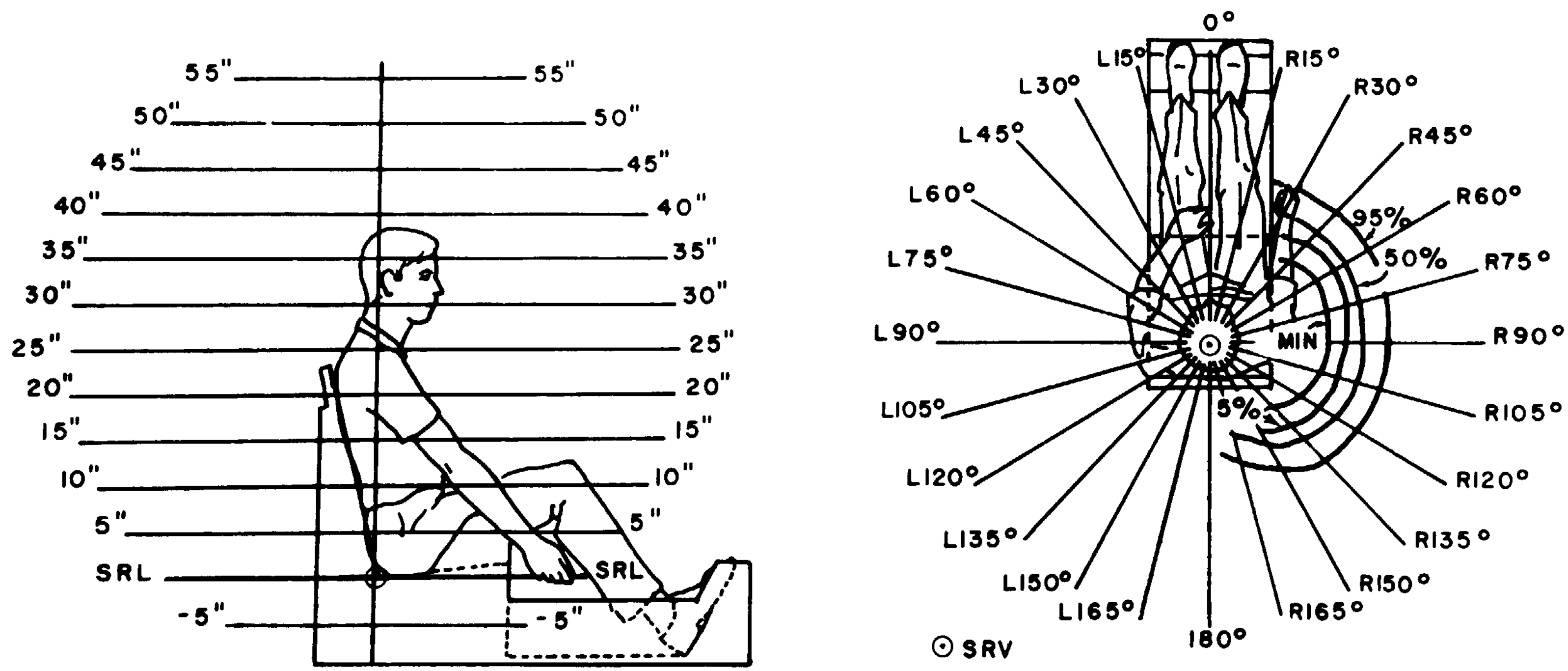


Figure 4. Men's grasping reach to a horizontal plane through the seat reference point.

TABLE 3
MEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE 12.5 CENTIMETERS (5 in.) ABOVE THE SEAT REFERENCE POINT. HORIZONTAL DISTANCE FROM THE SRV*
See Figure 5

Angle to Left or Right	Minimum		Percentiles 5		50		95	
L 165								
L 150								
L 135								
L 120								
L 105								
L 90								
L 75								
L 60								
L 45								
L 30								
L 15								
0								
R 15								
R 30	55.9	(22.0)	60.2	(23.7)	66.0	(26.0)	74.9	(29.5)
R 45	59.7	(23.5)	64.0	(25.2)	69.1	(27.2)	76.2	(30.0)
R 60	60.2	(23.7)	65.3	(25.7)	70.4	(27.7)	76.2	(30.0)
R 75	61.0	(24.0)	65.3	(25.7)	69.9	(27.5)	76.7	(30.2)
R 90	61.0	(24.0)	65.3	(25.7)	69.9	(27.5)	78.0	(30.7)
R 105	60.2	(23.7)	64.0	(25.2)	68.6	(27.0)	76.2	(30.0)
R 120	58.4	(23.0)	62.2	(24.5)	67.3	(26.5)	73.7	(29.0)
R 135	54.6	(21.5)	57.7	(22.7)	63.5	(25.0)	71.1	(28.0)
R 150					56.4	(22.2)	65.3	(25.7)
R 165					48.8	(19.2)	53.8	(21.2)
180								

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

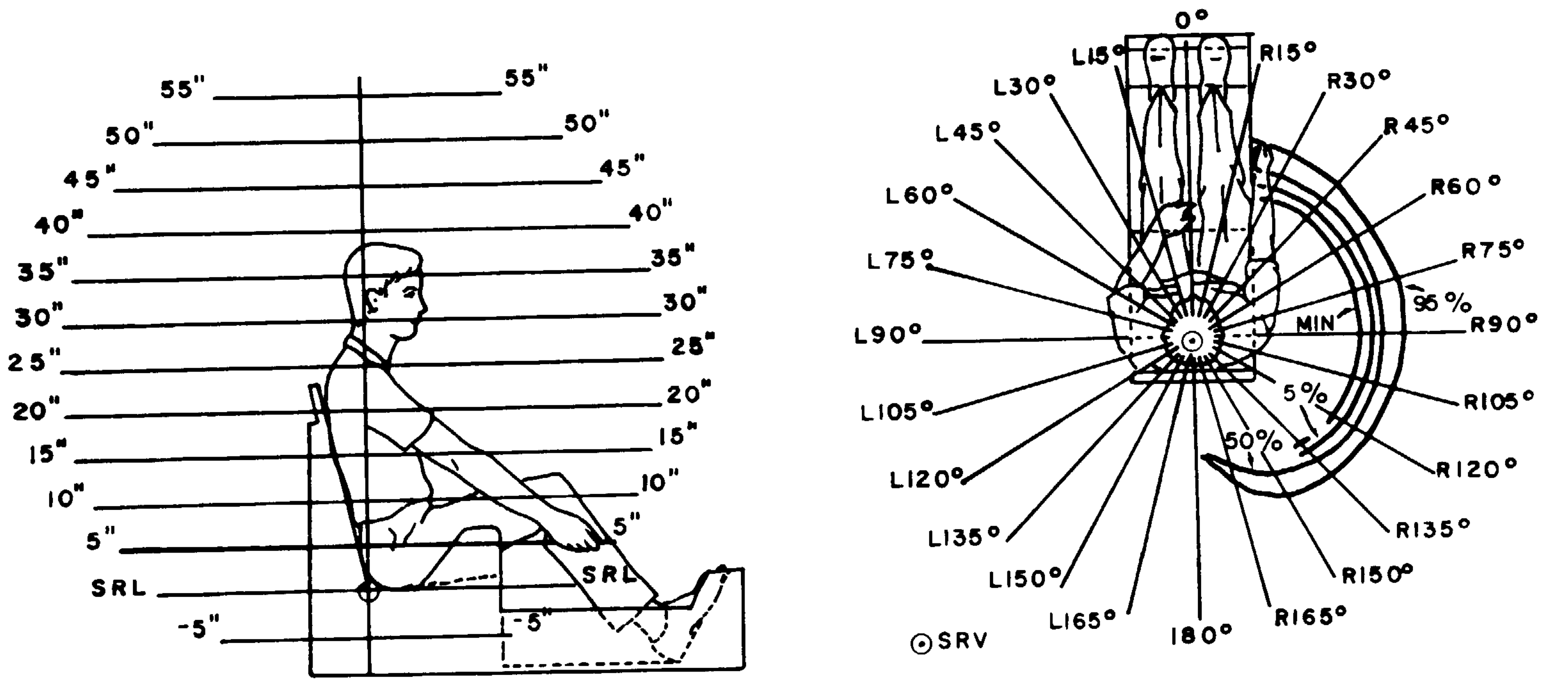


Figure 5. Men's grasping reach to a horizontal plane 5 inches above the seat reference point.

TABLE 4

MEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
25.4 CENTIMETERS (10 in.) ABOVE THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 6

Angle to Left or Right	Minimum		Percentiles 5		50		95	
L 165								
L 150								
L 135								
L 120								
L 105								
L 90							34.3	(13.5)
L 75							43.7	(17.2)
L 60					41.9	(16.5)	53.3	(21.0)
L 45					49.5	(19.5)	58.9	(23.2)
L 30					53.3	(21.0)	62.7	(24.7)
L 15					55.9	(22.0)	66.5	(26.2)
0								
R 15								
R 30	66.5	(26.2)	68.6	(27.0)	74.2	(29.2)	83.8	(33.0)
R 45	69.1	(27.2)	71.6	(28.2)	77.5	(30.5)	85.6	(33.7)
R 60	71.1	(28.0)	73.7	(29.0)	78.0	(30.7)	85.1	(33.5)
R 75	71.6	(28.2)	74.2	(29.2)	78.0	(30.7)	85.1	(33.5)
R 90	71.6	(28.2)	74.2	(29.2)	78.7	(31.0)	85.1	(33.5)
R 105	70.4	(27.7)	72.9	(28.7)	77.5	(30.5)	83.1	(32.7)
R 120	67.8	(26.7)	70.4	(27.7)	75.4	(29.7)	80.0	(31.5)
R 135			66.5	(26.2)	71.6	(28.2)	78.0	(30.7)
R 150					64.0	(25.2)	72.9	(28.7)
R 165								
180								

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

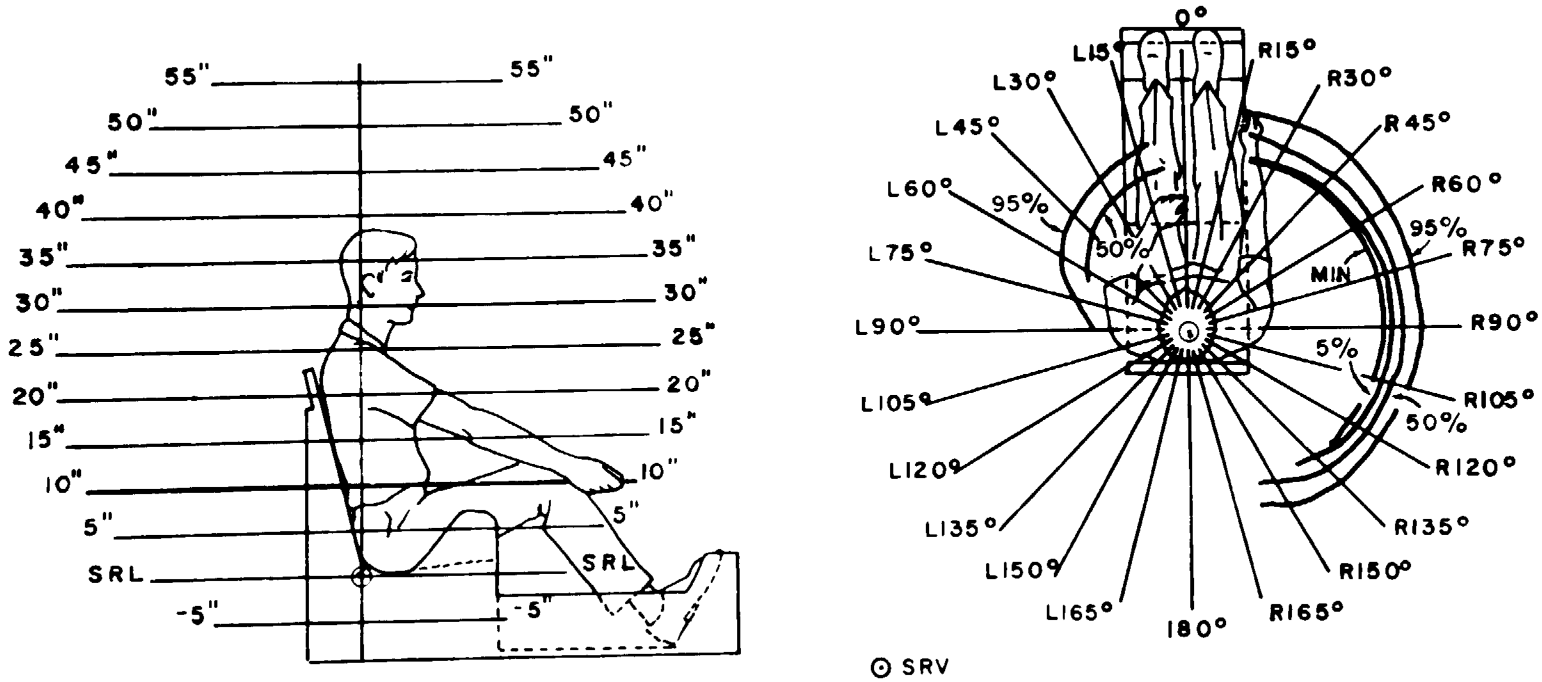


Figure 6. Men's grasping reach to a horizontal plane 10 inches above the seat reference point.

TABLE 5

MEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
38.1 CENTIMETERS (15 in.) ABOVE THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 7

Angle to Left or Right	Minimum		Percentiles 5		50		95	
L 165								
L 150								
L 135								
L 120								
L 105								
L 90							44.5	(17.5)
L 75							50.8	(20.0)
L 60					48.8	(19.2)	58.4	(23.0)
L 45			48.3	(19.0)	54.6	(21.5)	65.3	(25.7)
L 30	53.3	(21.0)	55.1	(21.7)	61.0	(24.0)	69.1	(27.2)
L 15	57.2	(22.5)	58.9	(23.2)	66.0	(26.0)	72.9	(28.7)
0	61.5	(24.2)	62.7	(24.7)	72.9	(28.7)	78.7	(31.0)
R 15	66.0	(26.0)	67.3	(26.5)	77.5	(30.5)	86.4	(34.0)
R 30	71.6	(28.2)	72.4	(28.5)	80.0	(31.5)	88.9	(35.0)
R 45	74.9	(29.5)	76.2	(30.0)	83.1	(32.7)	90.2	(35.5)
R 60	76.2	(30.0)	78.7	(31.0)	82.6	(32.5)	88.1	(34.7)
R 75	76.2	(30.0)	80.0	(31.5)	82.6	(32.5)	88.1	(34.7)
R 90	76.7	(30.2)	78.7	(31.0)	82.6	(32.5)	88.1	(34.7)
R 105	76.2	(30.0)	78.0	(30.7)	81.8	(32.2)	87.6	(34.5)
R 120	73.7	(29.0)	74.9	(29.5)	81.3	(32.0)	85.6	(33.7)
R 135					76.2	(30.0)	82.6	(32.5)
R 150							74.9	(29.5)
R 165								
180								

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

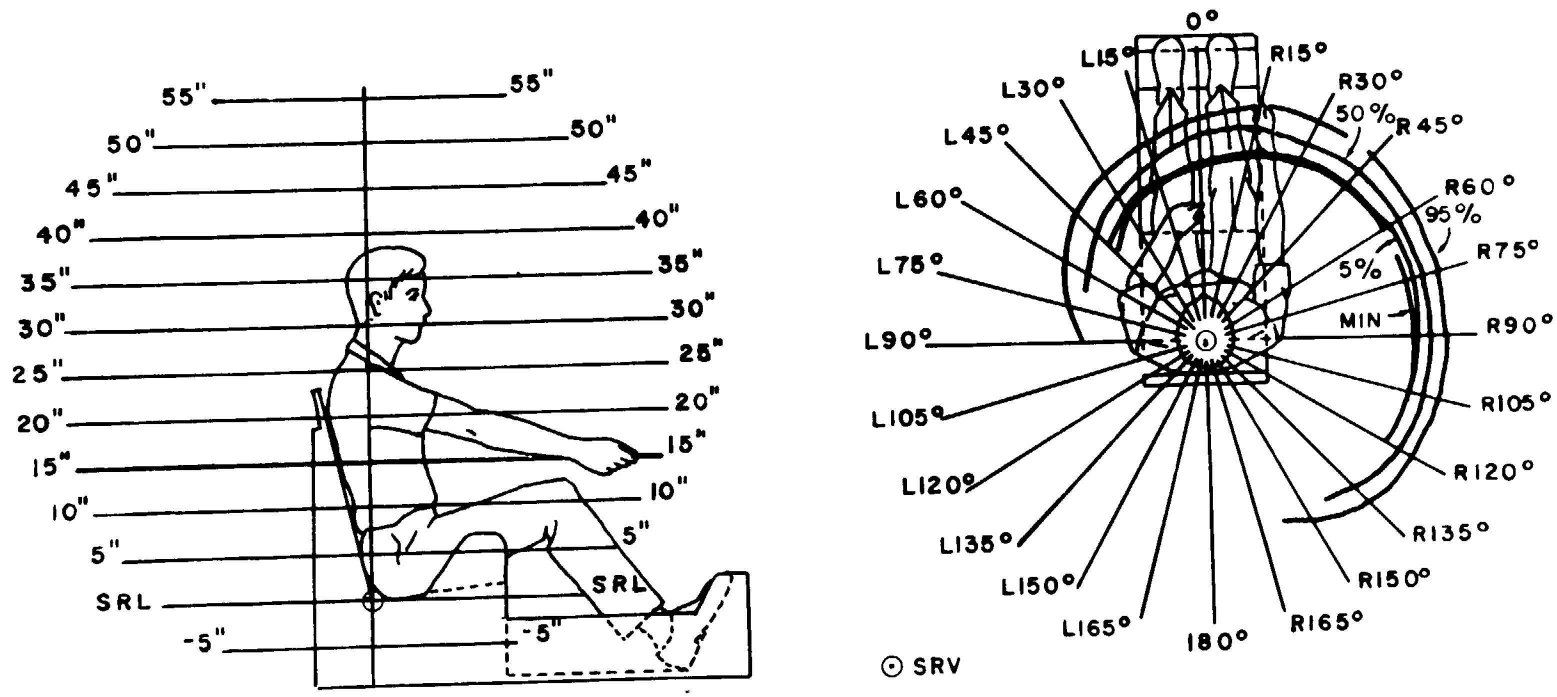


Figure 7. Men's grasping reach to a horizontal plane 15 inches above the seat reference point.

TABLE 6

MEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
50.8 CENTIMETERS (20 in.) ABOVE THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 8

Angle to Left or Right	Minimum		Percentiles 5		50		95	
L 165								
L 150								
L 135								
L 120								
L 105								
L 90					35.6	(14.0)	47.5	(18.7)
L 75					45.7	(18.0)	54.6	(21.5)
L 60	43.2	(17.0)	44.5	(17.5)	52.1	(20.5)	62.2	(24.5)
L 45	46.2	(18.2)	49.5	(19.5)	57.7	(22.7)	67.8	(26.7)
L 30	51.3	(20.2)	54.6	(21.5)	62.7	(24.7)	71.6	(28.2)
L 15	57.2	(22.5)	59.7	(23.5)	67.8	(26.7)	75.4	(29.7)
0	63.5	(25.0)	64.8	(25.5)	72.9	(28.7)	80.5	(31.7)
R 15	69.1	(27.2)	71.1	(28.0)	77.5	(30.5)	86.4	(34.0)
R 30	73.7	(29.0)	76.2	(30.0)	81.3	(32.0)	90.7	(35.7)
R 45	77.5	(30.5)	78.7	(31.0)	85.1	(33.5)	91.9	(36.2)
R 60	80.0	(31.5)	81.3	(32.0)	85.6	(33.7)	91.9	(36.2)
R 75	80.0	(31.5)	81.8	(32.2)	86.4	(34.0)	92.7	(36.5)
R 90	80.5	(31.7)	81.8	(32.2)	86.4	(34.0)	91.4	(36.0)
R 105	80.0	(31.5)	80.5	(31.7)	85.1	(33.5)	90.7	(35.7)
R 120			77.5	(30.5)	83.8	(33.0)	90.2	(35.5)
R 135							87.6	(34.5)
R 150								
R 165								
180								

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

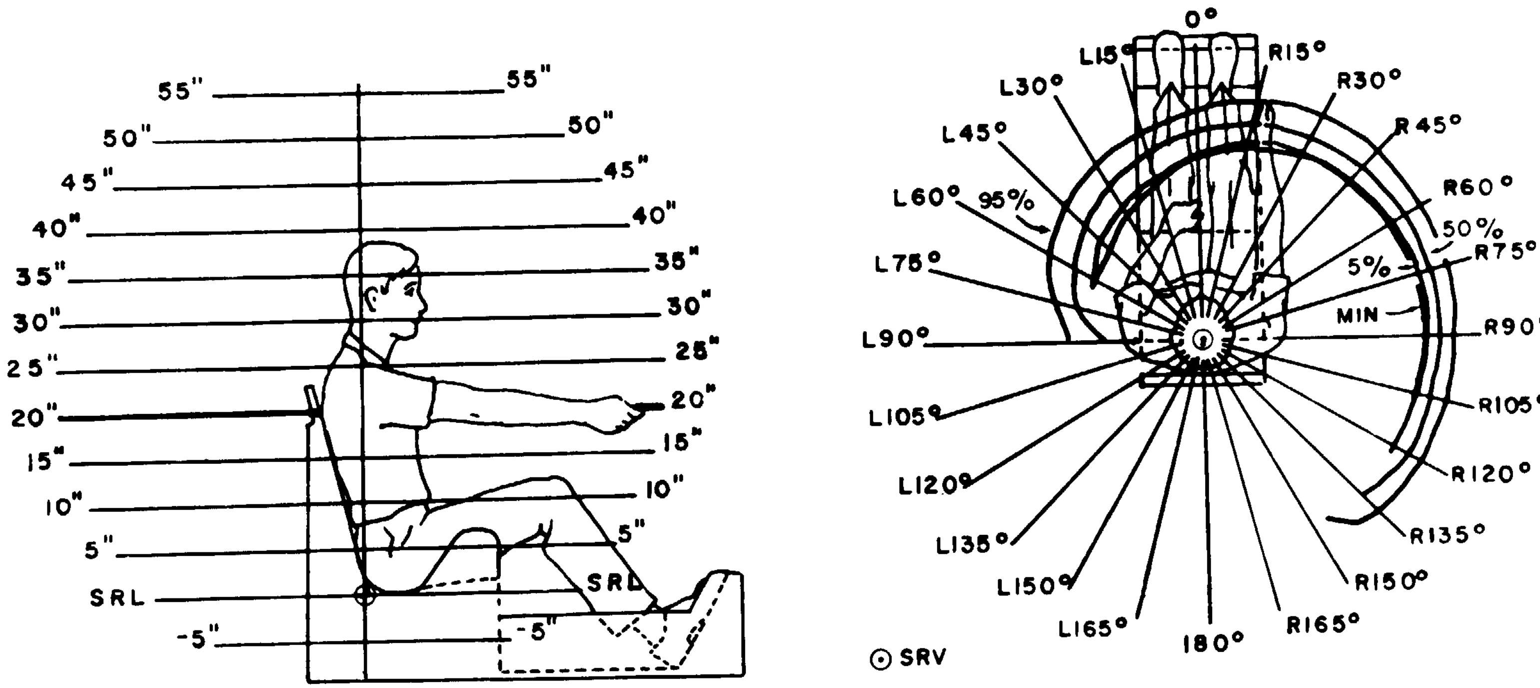


Figure 8. Men's grasping reach to a horizontal plane 20 inches above the seat reference point.

TABLE 7

MEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
63.5 CENTIMETERS (25 in.) ABOVE THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 9

Angle to Left or Right	Minimum		Percentiles 5		50		95	
L 165								
L 150								
L 135								
L 120								
L 105							45.0	(17.7)
L 90					39.9	(15.7)	51.3	(20.2)
L 75					48.8	(19.2)	56.4	(22.2)
L 60	45.0	(17.7)	46.2	(18.2)	54.6	(21.5)	62.7	(24.7)
L 45	48.8	(19.2)	50.8	(20.0)	58.9	(23.2)	69.1	(27.2)
L 30	54.6	(21.5)	57.2	(22.5)	63.5	(25.0)	72.4	(28.5)
L 15	58.9	(23.2)	61.0	(24.0)	68.6	(27.0)	75.4	(29.7)
0	63.5	(25.0)	66.5	(26.2)	72.4	(28.5)	80.0	(31.5)
R 15	69.1	(27.2)	71.6	(28.2)	76.7	(30.2)	85.1	(33.5)
R 30	74.2	(29.2)	76.7	(30.2)	82.6	(32.5)	89.4	(35.2)
R 45	77.5	(30.5)	78.7	(31.0)	85.1	(33.5)	90.7	(35.7)
R 60	78.7	(31.0)	80.0	(31.5)	85.6	(33.7)	94.0	(37.0)
R 75	80.0	(31.5)	81.3	(32.0)	85.1	(33.5)	92.7	(36.5)
R 90	80.5	(31.7)	81.8	(32.2)	85.6	(33.7)	91.9	(36.2)
R 105	79.2	(31.2)	80.0	(31.5)	85.1	(33.5)	91.4	(36.0)
R 120			77.5	(30.5)	84.3	(33.2)	90.2	(35.5)
R 135							88.9	(35.0)
R 150								
R 165								
180								

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

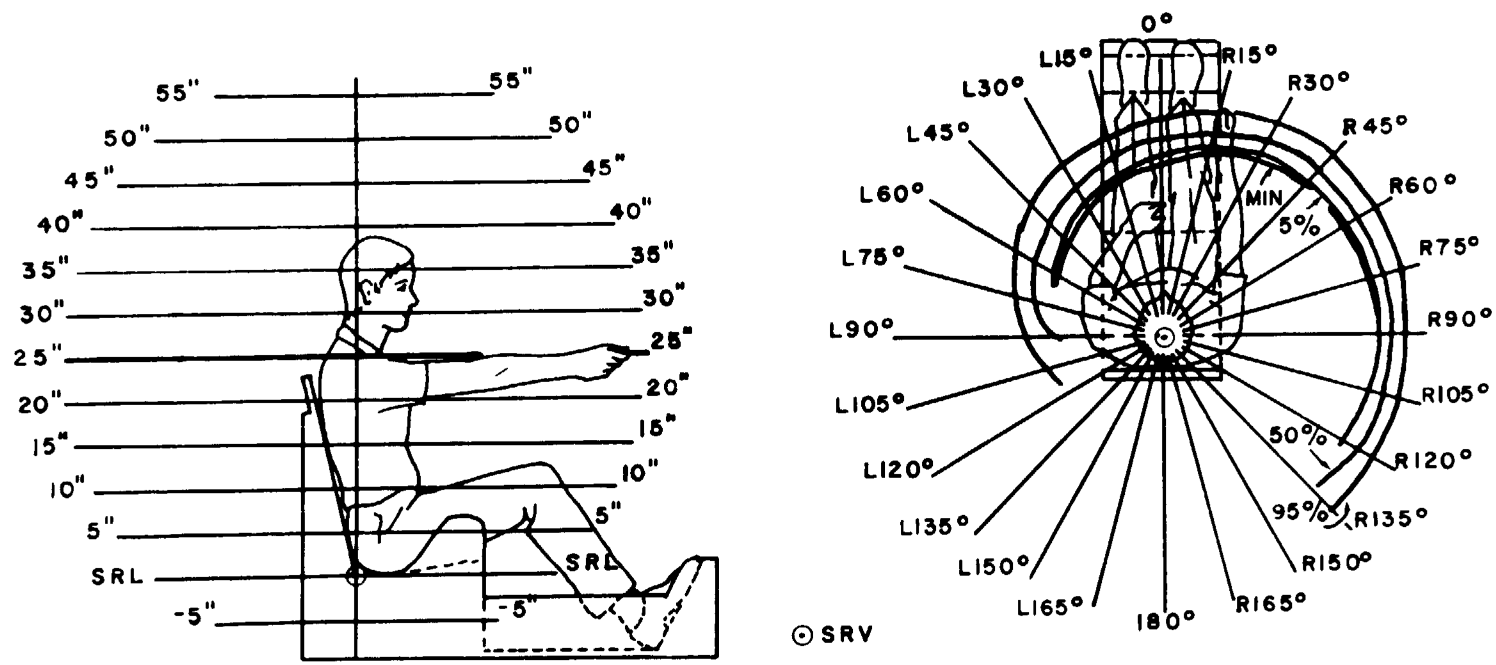


Figure 9. Men's grasping reach to a horizontal plane 25 inches above the seat reference point.

TABLE 8

MEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
76.2 CENTIMETERS (30 in.) ABOVE THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 10

Angle to Left or Right	Minimum		Percentiles 5		50		95	
L 165							47.5	(18.7)
L 150							48.8	(19.2)
L 135							50.8	(20.0)
L 120							47.5	(18.7)
L 105							48.3	(19.0)
L 90					42.4	(16.7)	52.6	(20.7)
L 75					47.5	(18.7)	57.2	(22.5)
L 60	43.2	(17.0)	43.7	(17.2)	52.6	(20.7)	62.2	(24.5)
L 45	46.2	(18.2)	48.3	(19.0)	57.2	(22.5)	67.3	(26.5)
L 30	50.0	(19.7)	54.6	(21.5)	62.2	(24.5)	71.6	(28.2)
L 15	55.9	(22.0)	60.2	(23.7)	67.8	(26.7)	74.9	(29.5)
0	60.2	(23.7)	64.8	(25.5)	72.4	(28.5)	78.7	(31.0)
R 15	66.0	(26.0)	69.1	(27.2)	75.4	(29.7)	83.8	(33.0)
R 30	70.4	(27.7)	73.7	(29.0)	80.0	(31.5)	86.9	(34.2)
R 45	72.9	(28.7)	76.7	(30.2)	81.8	(32.2)	88.1	(34.7)
R 60	76.2	(30.0)	78.7	(31.0)	83.1	(32.7)	90.7	(35.7)
R 75	78.0	(30.7)	79.2	(31.2)	83.8	(33.0)	90.2	(35.5)
R 90	78.7	(31.0)	79.2	(31.2)	84.3	(33.2)	90.7	(35.7)
R 105	78.0	(30.7)	78.7	(31.0)	83.8	(33.0)	89.4	(35.2)
R 120			76.7	(30.2)	82.6	(32.5)	88.1	(34.7)
R 135							87.6	(34.5)
R 150								
R 165							49.5	(19.5)
180							51.3	(20.2)

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

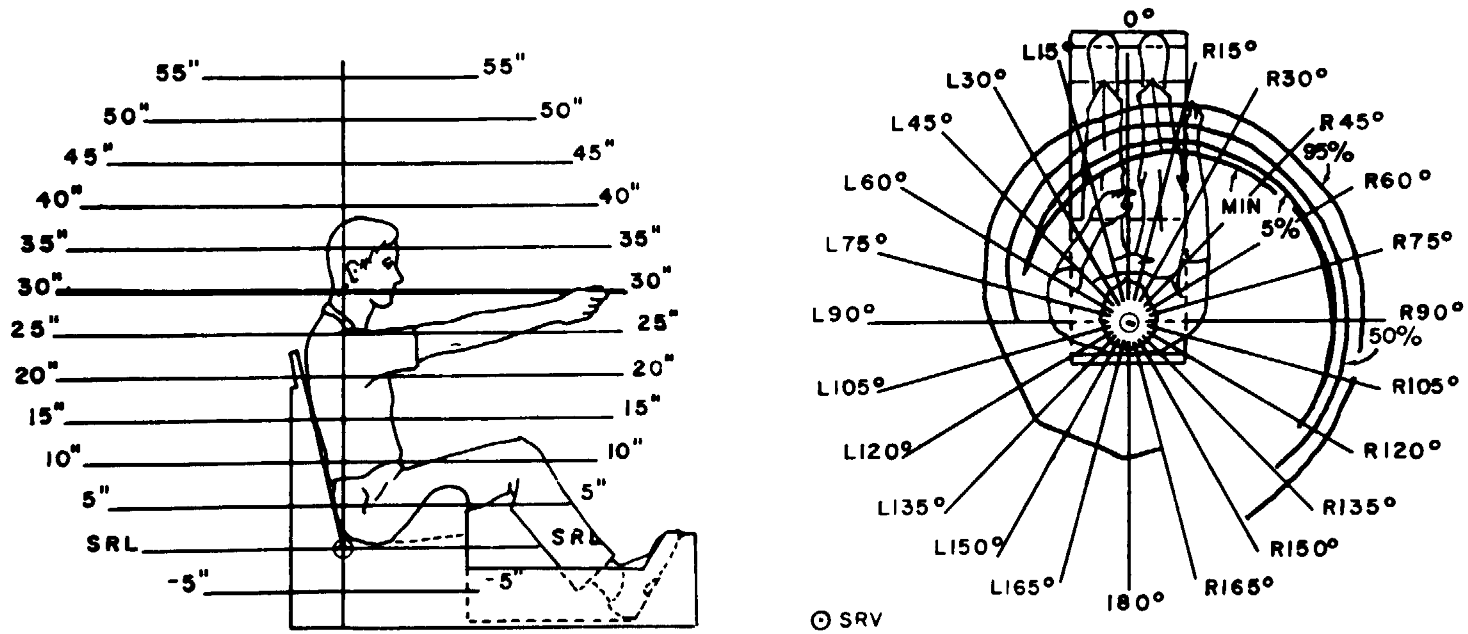


Figure 10. Men's grasping reach to a horizontal plane 30 inches above the seat reference point.

TABLE 9

MEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
88.9 CENTIMETERS (35 in.) ABOVE THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 11

Angle to Left or Right	Minimum		Percentiles 5		50		95	
L 165					37.3	(14.7)	53.3	(21.0)
L 150					34.8	(13.7)	50.8	(20.0)
L 135					33.5	(13.2)	48.3	(19.0)
L 120			27.2	(10.7)	33.5	(13.2)	47.5	(18.7)
L 105			31.0	(12.2)	35.6	(14.0)	47.5	(18.7)
L 90	32.3	(12.7)	34.8	(13.7)	39.4	(15.5)	50.8	(20.0)
L 75	36.1	(14.2)	38.1	(15.0)	43.7	(17.2)	53.3	(21.0)
L 60	38.6	(15.2)	40.6	(16.0)	47.5	(18.7)	54.6	(21.5)
L 45	41.1	(16.2)	43.7	(17.2)	52.1	(20.5)	62.7	(24.7)
L 30	45.7	(18.0)	48.8	(19.2)	57.2	(22.5)	66.5	(26.2)
L 15	48.8	(19.2)	53.3	(21.0)	62.7	(24.7)	68.6	(27.0)
0	52.6	(20.7)	56.4	(22.2)	67.3	(26.5)	72.4	(28.5)
R 15	57.7	(22.7)	62.7	(24.7)	70.4	(27.7)	78.7	(31.0)
R 30	62.2	(24.5)	67.8	(26.7)	74.2	(29.2)	83.1	(32.7)
R 45	67.8	(26.7)	71.6	(28.2)	77.5	(30.5)	85.6	(33.7)
R 60	71.1	(28.0)	73.7	(29.0)	78.7	(31.0)	85.6	(33.7)
R 75	72.9	(28.7)	74.9	(29.5)	79.2	(31.2)	86.4	(34.0)
R 90	73.7	(29.0)	75.4	(29.7)	79.2	(31.2)	85.1	(33.5)
R 105	73.7	(29.0)	75.4	(29.7)	80.0	(31.5)	85.1	(33.5)
R 120	72.4	(28.5)	73.7	(29.0)	78.7	(31.0)	85.1	(33.5)
R 135					72.39	(28.5)	85.1	(33.5)
R 150							80.0	(31.5)
R 165							55.1	(21.7)
180					41.9	(16.5)	56.4	(22.2)

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

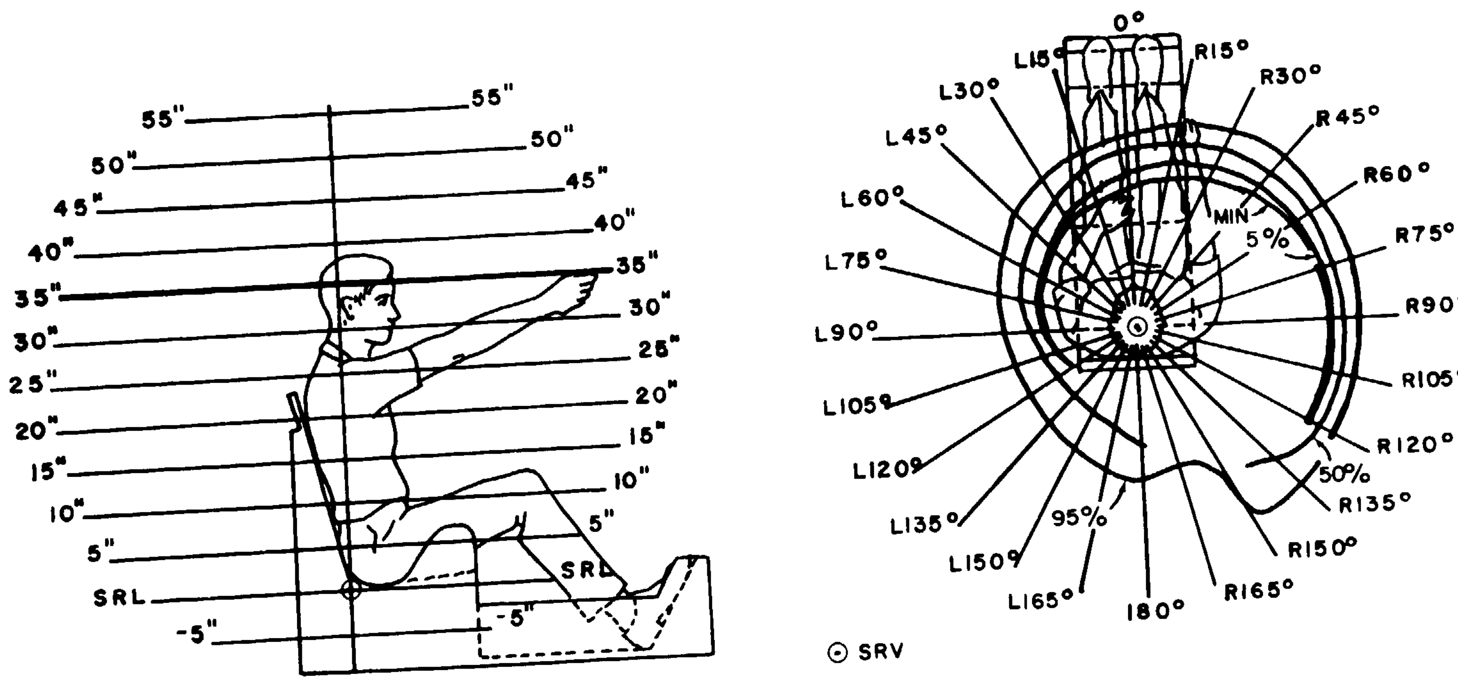


Figure 11. Men's grasping reach to a horizontal plane 35 inches above the seat reference point.

TABLE 10

MEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
101.6 CENTIMETERS (40 in.) ABOVE THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 12

Angle to Left or Right	Minimum		Percentiles 5		50		95	
L 165					39.4	(15.5)	54.6	(21.5)
L 150					37.3	(14.7)	50.8	(20.0)
L 135					35.6	(14.0)	48.8	(19.2)
L 120			28.4	(11.2)	33.5	(13.2)	47.0	(18.5)
L 105			29.7	(11.7)	33.5	(13.2)	46.2	(18.2)
L 90	30.5	(12.0)	31.0	(12.2)	34.8	(13.7)	46.2	(18.2)
L 75	31.0	(12.2)	31.8	(12.5)	38.1	(15.0)	47.5	(18.7)
L 60	31.8	(12.5)	33.5	(13.2)	41.1	(16.2)	50.8	(20.0)
L 45	33.0	(13.0)	35.6	(14.0)	45.0	(17.7)	54.6	(21.5)
L 30	34.8	(13.7)	39.4	(15.5)	49.5	(19.5)	59.7	(23.5)
L 15	38.6	(15.2)	43.2	(17.0)	53.8	(21.2)	62.2	(24.5)
0	43.2	(17.0)	48.3	(19.0)	58.4	(23.0)	65.3	(25.7)
R 15	47.5	(18.7)	53.3	(21.0)	62.2	(24.5)	72.4	(28.5)
R 30	53.3	(21.0)	57.7	(22.7)	66.5	(26.2)	77.5	(30.5)
R 45	58.9	(23.2)	62.7	(24.7)	70.4	(27.7)	80.0	(31.5)
R 60	61.5	(24.2)	64.8	(25.5)	71.1	(28.0)	79.2	(31.2)
R 75	63.5	(25.0)	66.0	(26.0)	71.1	(28.0)	80.0	(31.5)
R 90	63.5	(25.0)	66.5	(26.2)	71.6	(28.2)	80.0	(31.5)
R 105	65.3	(25.7)	67.8	(26.7)	72.4	(28.5)	80.5	(31.7)
R 120			66.5	(26.2)	72.9	(28.7)	80.0	(31.5)
R 135					68.6	(27.0)	78.7	(31.0)
R 150							74.2	(29.2)
R 165					42.4	(16.7)	60.2	(23.7)
180					45.0	(17.7)	59.7	(23.5)

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

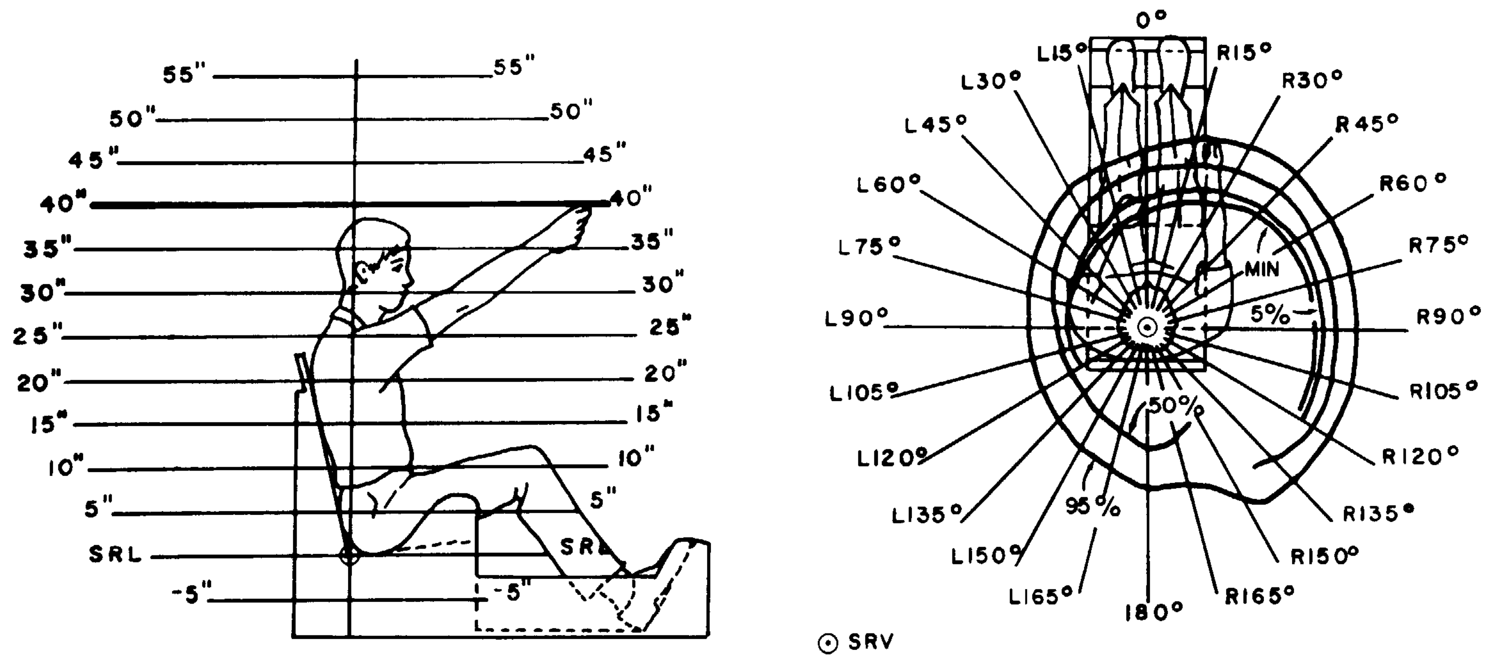


Figure 12. Men's grasping reach to a horizontal plane 40 inches above the seat reference point.

TABLE 11
MEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
114.3 CENTIMETERS (45 in.) ABOVE THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 13

Angle to Left or Right	Minimum		Percentiles 5		50		95	
L 165			26.7	(10.5)	35.6	(14.0)	50.8	(20.0)
L 150	21.6	(8.5)	22.1	(8.7)	31.0	(12.2)	46.2	(18.2)
L 135	19.1	(7.5)	19.6	(7.7)	27.9	(11.0)	42.4	(16.7)
L 120	17.8	(7.0)	19.1	(7.5)	26.7	(10.5)	39.4	(15.5)
L 105	17.0	(6.7)	18.3	(7.2)	25.9	(10.2)	38.1	(15.0)
L 90	17.0	(6.7)	18.3	(7.2)	26.7	(10.5)	38.1	(15.0)
L 75	17.0	(6.7)	19.1	(7.5)	27.9	(11.0)	38.6	(15.2)
L 60	17.8	(7.0)	19.6	(7.7)	30.5	(12.0)	41.1	(16.2)
L 45	19.1	(7.5)	21.6	(8.5)	34.3	(13.5)	46.2	(18.2)
L 30	21.6	(8.5)	24.1	(9.5)	38.1	(15.0)	50.0	(19.7)
L 15	25.4	(10.0)	27.9	(11.0)	41.9	(16.5)	53.8	(21.2)
0	28.4	(11.2)	32.3	(12.7)	46.2	(18.2)	57.7	(22.7)
R 15	33.0	(13.0)	39.4	(15.5)	50.8	(20.0)	62.7	(24.7)
R 30	37.3	(14.7)	44.5	(17.5)	55.9	(22.0)	66.5	(26.2)
R 45	43.7	(17.2)	48.3	(19.0)	59.7	(23.5)	68.6	(27.0)
R 60	48.8	(19.2)	52.1	(20.5)	61.0	(24.0)	69.1	(27.2)
R 75	49.5	(19.5)	52.1	(20.5)	61.0	(24.0)	69.9	(27.5)
R 90	50.0	(19.7)	53.3	(21.0)	61.5	(24.2)	70.4	(27.7)
R 105	51.3	(20.2)	54.6	(21.5)	62.2	(24.5)	71.1	(28.0)
R 120	50.0	(19.7)	53.8	(21.2)	62.2	(24.5)	70.4	(27.7)
R 135	47.5	(18.7)	50.8	(20.0)	58.9	(23.2)	70.4	(27.7)
R 150			39.4	(15.5)	52.6	(20.7)	66.0	(26.0)
R 165			37.3	(14.7)	45.7	(18.0)	57.7	(22.7)
180			32.3	(12.7)	41.9	(16.5)	54.6	(21.5)

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

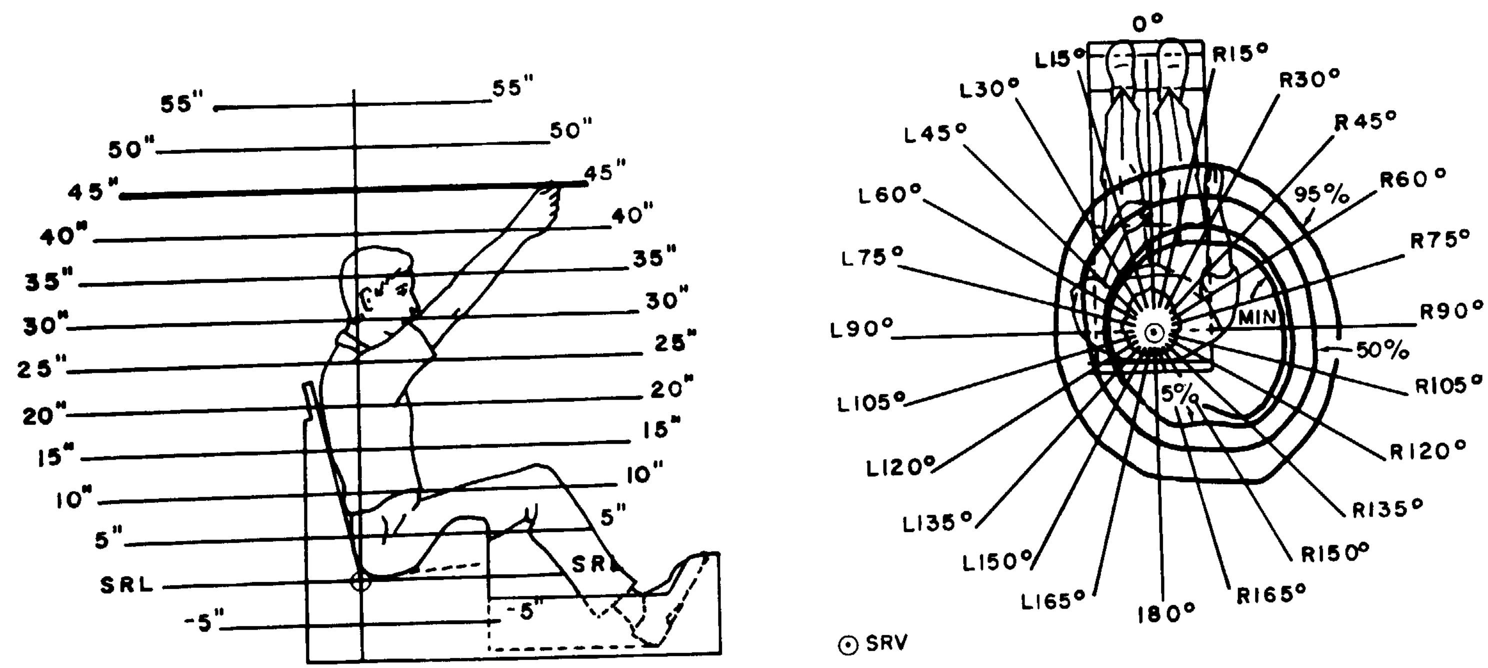


Figure 13. Men's grasping reach to a horizontal plane 45 inches above the seat reference point.

TABLE 12
WOMEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
THROUGH THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 14

Angle to Left or Right	Minimum	Percentiles 5		50		95	
L 165							
L 150							
L 135							
L 120							
L 105							
L 90							
L 75							
L 60							
L 45							
L 30							
L 15							
0							
R 15						55.9	(22.0)
R 30				41.1	(16.2)	55.1	(21.7)
R 45		35.6	(14.0)	44.5	(17.5)	56.4	(22.2)
R 60		38.6	(15.2)	47.5	(18.7)	58.4	(23.0)
R 75		41.1	(16.2)	48.3	(19.0)	60.2	(23.7)
R 90		42.4	(16.7)	49.5	(19.5)	60.2	(23.7)
R 105		40.6	(16.0)	48.3	(19.0)	58.4	(23.0)
R 120		38.6	(15.2)	46.2	(18.2)	55.9	(22.0)
R 135		33.0	(13.0)	41.9	(16.5)	52.1	(20.5)
R 150				33.0	(13.0)	47.5	(18.7)
R 165						39.9	(15.7)
180							

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

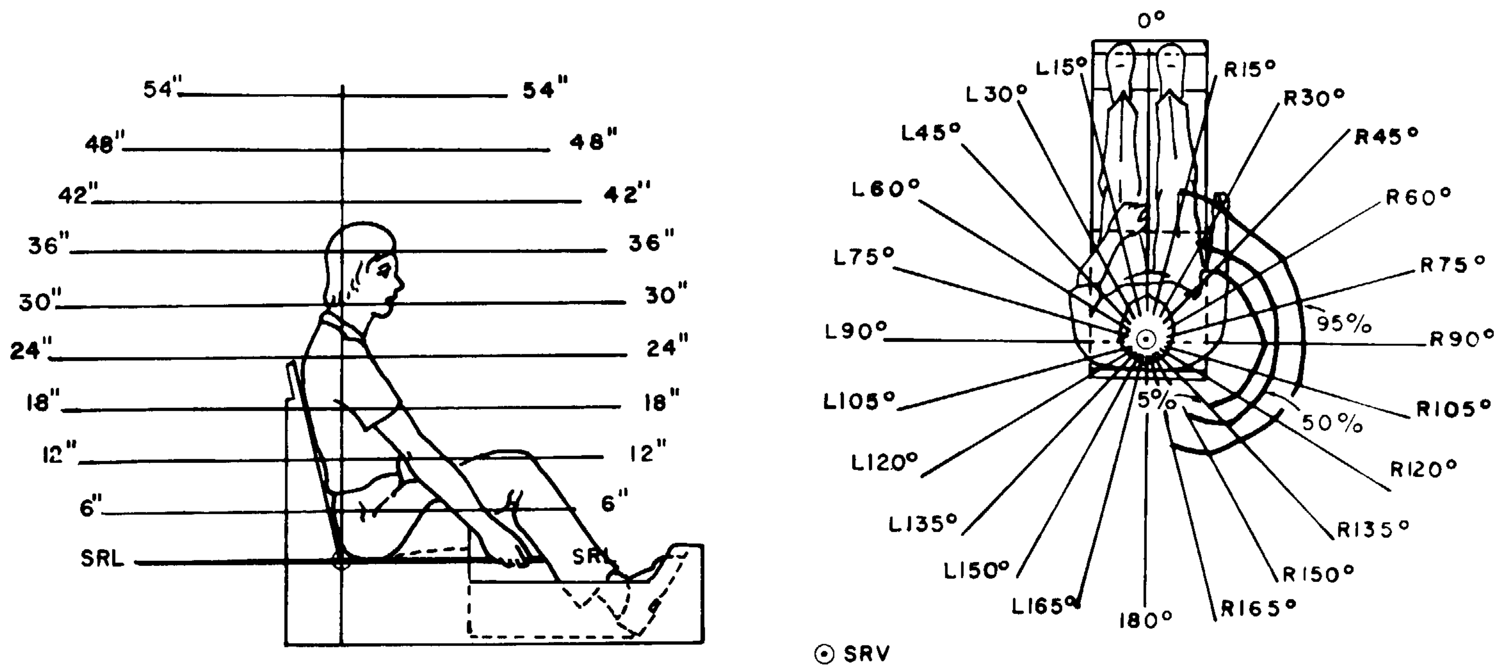


Figure 14. Women's grasping reach to a horizontal plane through the seat reference point.

TABLE 13

WOMEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE 15.2 CENTIMETERS (6 in.) ABOVE THE SEAT REFERENCE POINT. HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 15

Angle to Left or Right	Minimum	Percentiles					
		5		50		95	
L 165							
L 150							
L 135							
L 120							
L 105						26.7	(10.5)
L 90						29.2	(11.5)
L 75						36.8	(14.5)
L 60						40.6	(16.0)
L 45						45.7	(18.0)
L 30						50.8	(20.0)
L 15							
0							
R 15		50.8	(20.0)	57.2	(22.5)	67.3	(26.5)
R 30		53.3	(21.0)	58.4	(23.0)	69.9	(27.5)
R 45		54.6	(21.5)	60.2	(23.7)	71.1	(28.0)
R 60		58.9	(23.2)	63.5	(25.0)	71.1	(28.0)
R 75		60.2	(23.7)	63.5	(25.0)	72.4	(28.5)
R 90		60.2	(23.7)	64.0	(25.2)	72.4	(28.5)
R 105		58.9	(23.2)	63.5	(25.0)	70.4	(27.7)
R 120		55.9	(22.0)	61.0	(24.0)	66.5	(26.2)
R 135		52.6	(20.7)	58.4	(23.0)	64.8	(25.5)
R 150				50.8	(20.0)	61.0	(24.0)
R 165				41.1	(16.2)	53.3	(21.0)
180							

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

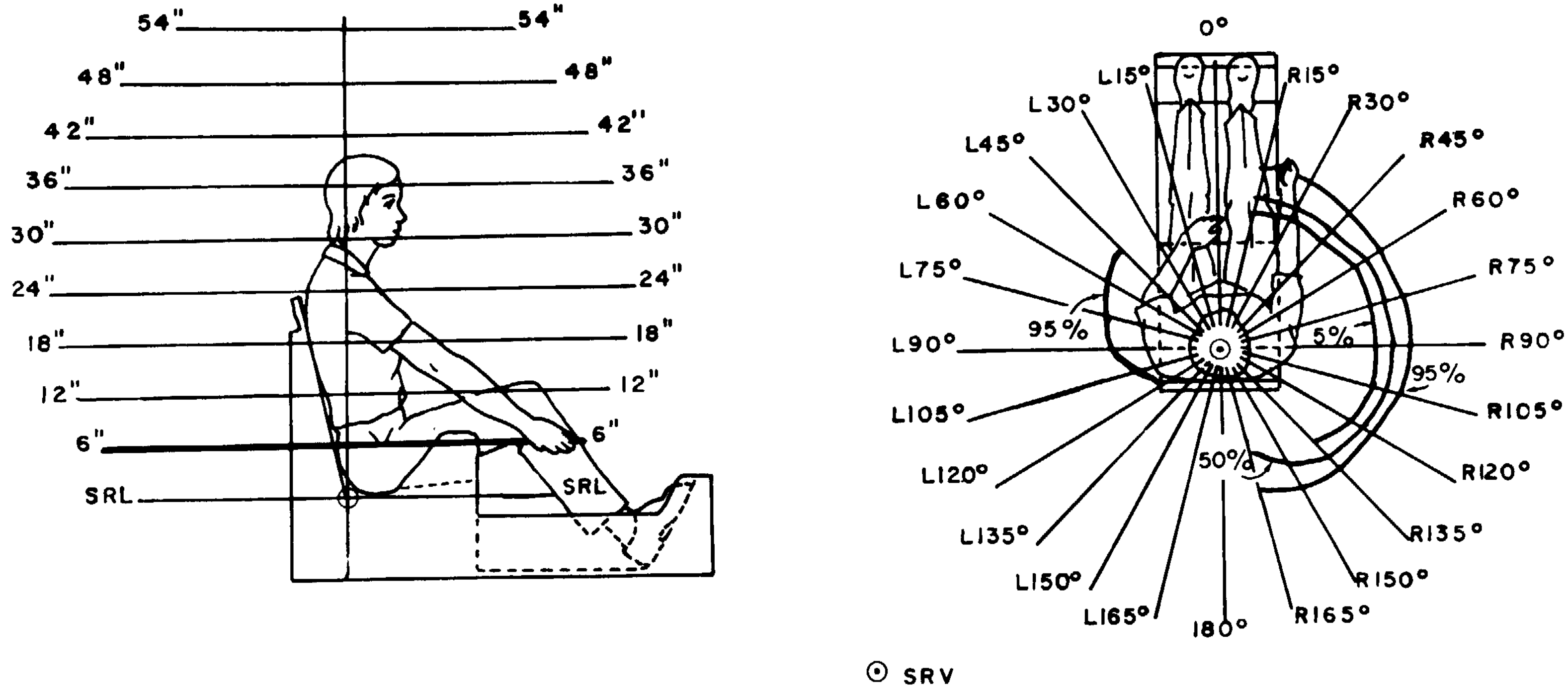


Figure 15. Women's grasping reach to a horizontal plane 6 inches above the seat reference point.

TABLE 14

WOMEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
30.5 CENTIMETERS (12 in.) ABOVE THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 16

Angle to Left or Right	Minimum	Percentiles 5		50		95	
L 165							
L 150							
L 135							
L 120						32.3	(12.7)
L 105						35.6	(14.0)
L 90				27.9	(11.0)	39.4	(15.5)
L 75				33.0	(13.0)	44.5	(17.5)
L 60		31.0	(12.2)	38.1	(15.0)	50.8	(20.0)
L 45		36.8	(14.5)	45.0	(17.7)	54.6	(21.5)
L 30		41.9	(16.5)	50.8	(20.0)	57.7	(22.7)
L 15		48.3	(19.0)	55.1	(21.7)	62.2	(24.5)
0		54.6	(21.5)	59.7	(23.5)	66.0	(26.0)
R 15		58.4	(23.0)	63.5	(25.0)	71.1	(28.0)
R 30		61.0	(24.0)	66.0	(26.0)	74.2	(29.2)
R 45		64.8	(25.5)	69.1	(27.2)	76.2	(30.0)
R 60		67.3	(26.5)	71.6	(28.2)	78.0	(30.7)
R 75		67.8	(26.7)	71.6	(28.2)	78.7	(31.0)
R 90		69.1	(27.2)	72.4	(28.5)	78.7	(31.0)
R 105		67.3	(26.5)	72.4	(28.5)	78.7	(31.0)
R 120				69.9	(27.5)	74.9	(29.5)
R 135				64.8	(25.5)	71.6	(28.2)
R 150				48.3	(19.0)	63.5	(25.0)
R 165						57.2	(22.5)
180							

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

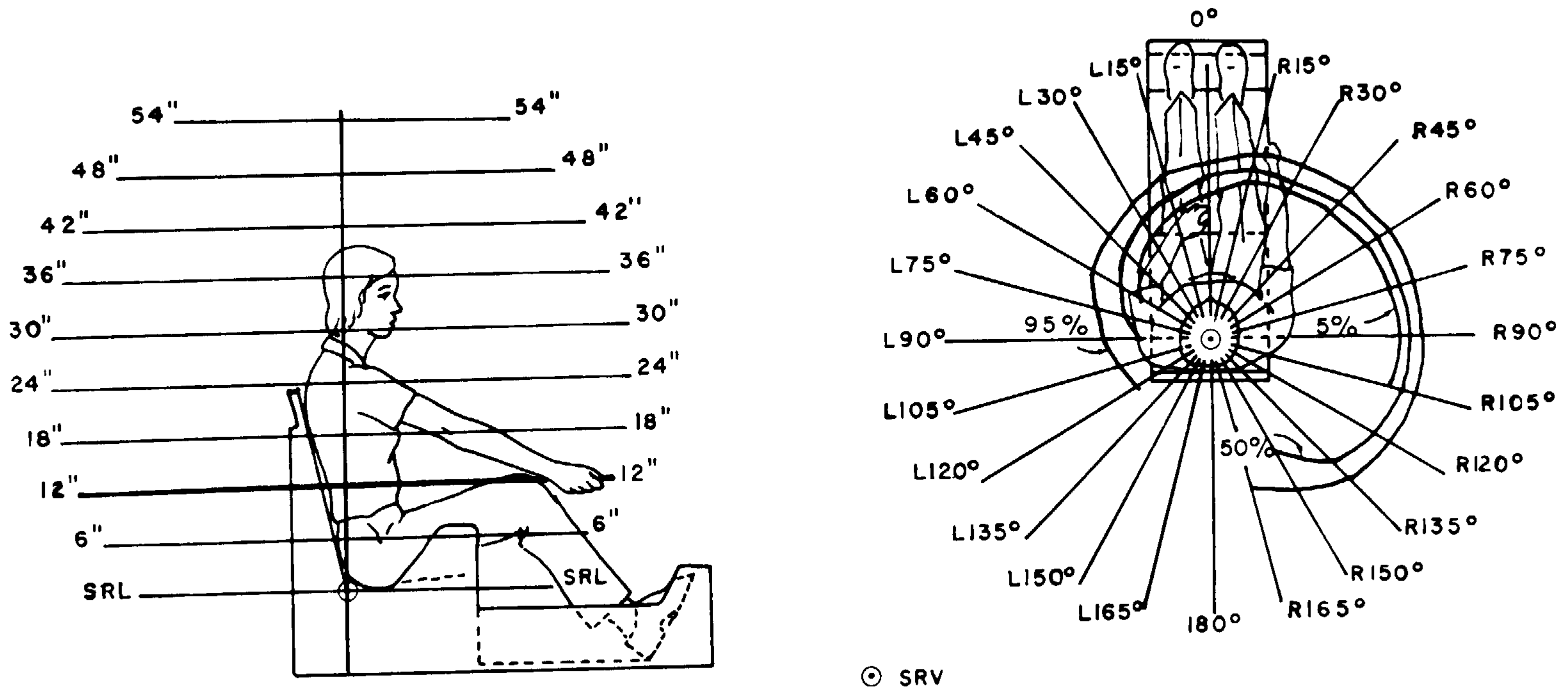


Figure 16. Women's grasping reach to a horizontal plane
12 inches above the seat reference point.

TABLE 15

WOMEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
45 CENTIMETERS (18 in.) ABOVE THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 17

Angle to Left or Right	Minimum	Percentiles 5		50		95	
L 165							
L 150							
L 135							
L 120						35.6	(14.0)
L 105				27.9	(11.0)	39.4	(15.5)
L 90		26.7	(10.5)	33.0	(13.0)	43.7	(17.2)
L 75		29.7	(11.7)	38.1	(15.0)	50.0	(19.7)
L 60		35.6	(14.0)	45.0	(17.7)	53.3	(21.0)
L 45		42.4	(16.7)	50.0	(19.7)	58.4	(23.0)
L 30		47.5	(18.7)	54.6	(21.5)	61.5	(24.2)
L 15		50.8	(20.0)	58.4	(23.0)	66.0	(26.0)
0		57.2	(22.5)	62.7	(24.7)	69.9	(27.5)
R 15		61.5	(24.2)	66.5	(26.2)	74.9	(29.5)
R 30		64.8	(25.5)	69.9	(27.5)	76.7	(30.2)
R 45		67.8	(26.7)	72.9	(28.7)	78.7	(31.0)
R 60		70.4	(27.7)	74.9	(29.5)	81.3	(32.0)
R 75		70.4	(27.7)	75.4	(29.7)	81.3	(32.0)
R 90		71.1	(28.0)	76.2	(30.0)	80.5	(31.7)
R 105		69.9	(27.5)	76.7	(30.2)	81.8	(32.2)
R 120				72.9	(28.7)	78.7	(31.0)
R 135						71.6	(28.2)
R 150						38.1	(15.0)
R 165							
180							

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

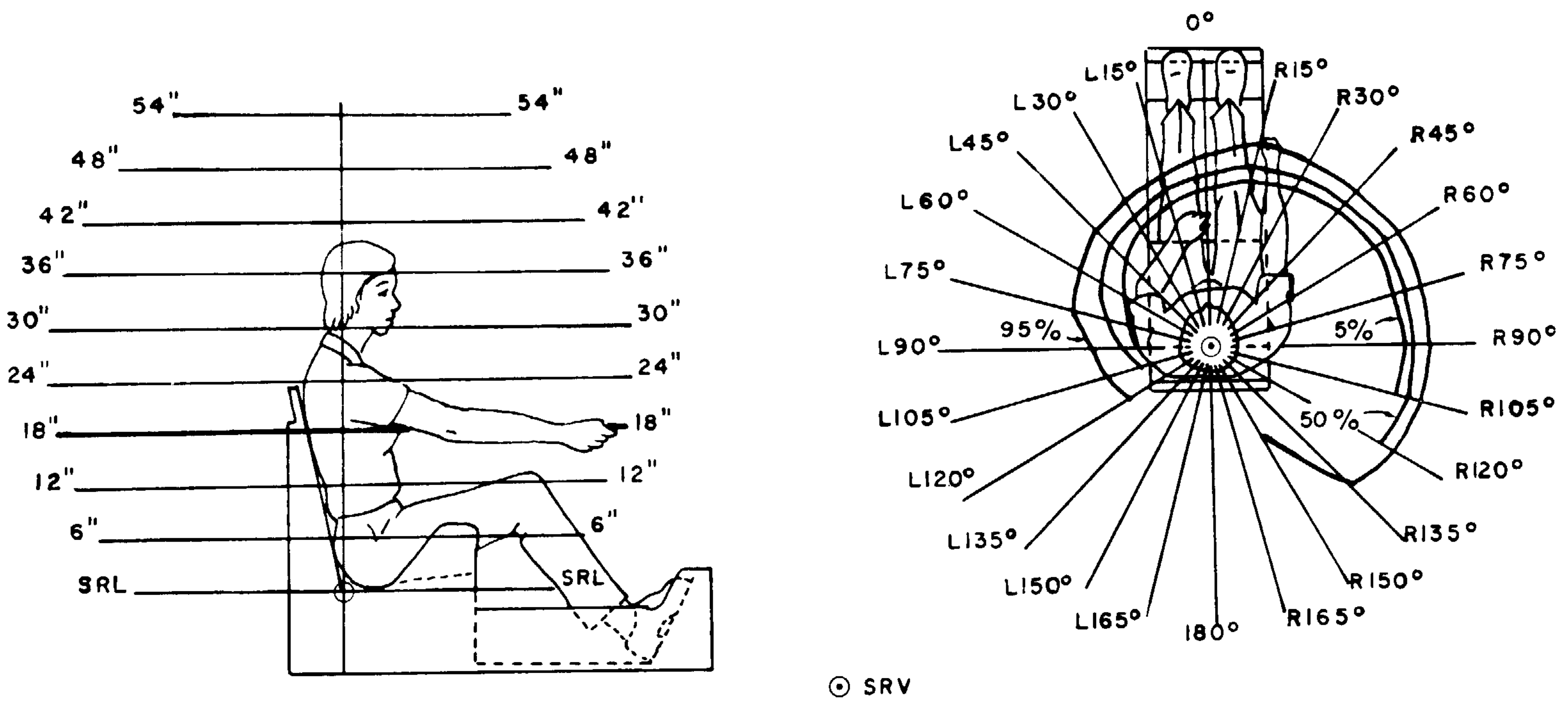


Figure 17. Women's grasping reach to a horizontal plane 18 inches above the seat reference point.

TABLE 16

WOMEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE 61 CENTIMETERS (24 in.) ABOVE THE SEAT REFERENCE POINT. HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 18

Angle to Left or Right	Minimum	Percentiles 5		50		95	
L 165				22.9	(9.0)	38.1	(15.0)
L 150				22.9	(9.0)	40.6	(16.0)
L 135				27.2	(10.7)	35.6	(14.0)
L 120				25.4	(10.0)	42.4	(16.7)
L 105		20.3	(8.0)	31.0	(12.2)	48.3	(19.0)
L 90		25.4	(10.0)	37.3	(14.7)	45.0	(17.7)
L 75		29.2	(11.5)	40.6	(16.0)	53.3	(21.0)
L 60		36.1	(14.2)	47.0	(18.5)	54.6	(21.5)
L 45		43.2	(17.0)	50.8	(20.0)	59.7	(23.5)
L 30		48.3	(19.0)	55.1	(21.7)	62.7	(24.7)
L 15		52.1	(20.5)	58.4	(23.0)	66.0	(26.0)
0		55.9	(22.0)	63.5	(25.0)	71.1	(28.0)
R 15		59.7	(23.5)	66.5	(26.2)	74.9	(29.5)
R 30		63.5	(25.0)	69.9	(27.5)	76.7	(30.2)
R 45		66.5	(26.2)	72.4	(28.5)	78.7	(31.0)
R 60		67.8	(26.7)	74.2	(29.2)	81.3	(32.0)
R 75		68.6	(27.0)	76.2	(30.0)	81.3	(32.0)
R 90		69.9	(27.5)	77.5	(30.5)	81.3	(32.0)
R 105		69.1	(27.2)	76.7	(30.2)	81.8	(32.2)
R 120		33.0	(13.0)	72.4	(28.5)	78.7	(31.0)
R 135		27.9	(11.0)	35.6	(14.0)	68.6	(27.0)
R 150		22.9	(9.0)	30.5	(12.0)	55.9	(22.0)
R 165		20.8	(8.2)	28.4	(11.2)	45.7	(18.0)
180				27.9	(11.0)	40.6	(16.0)

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

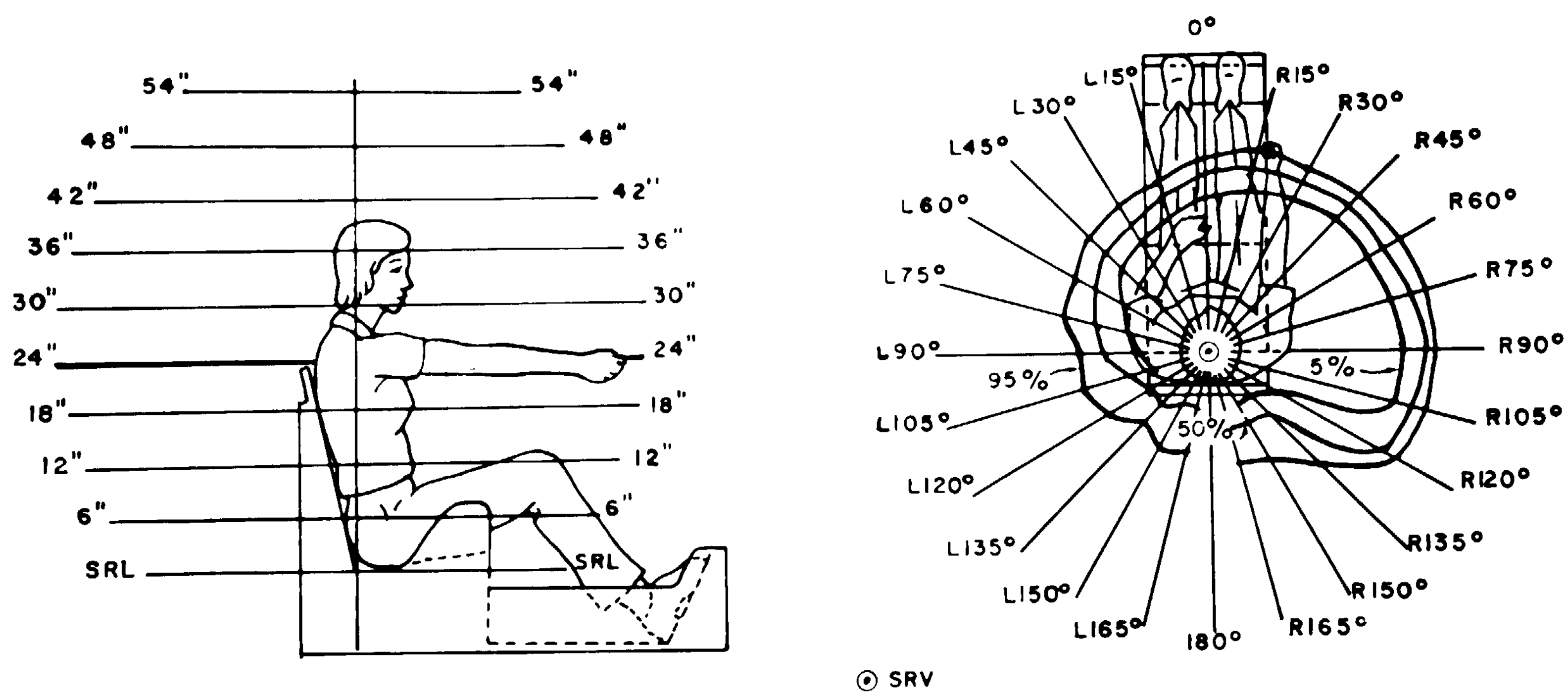


Figure 18. Women's grasping reach to a horizontal plane 24 inches above the seat reference point.

TABLE 17

WOMEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
76.2 CENTIMETERS (30 in.) ABOVE THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 19

Angle to Left or Right	Minimum	Percentiles					
		5		50		95	
L 165		18.3	(7.2)	31.8	(12.5)	48.8	(19.2)
L 150		15.7	(6.2)	30.5	(12.0)	41.9	(16.5)
L 135		17.0	(6.7)	22.1	(8.7)	38.6	(15.2)
L 120		17.8	(7.0)	27.2	(10.7)	43.2	(17.0)
L 105		16.5	(6.5)	30.5	(12.0)	45.7	(18.0)
L 90		22.1	(8.7)	33.0	(13.0)	43.7	(17.2)
L 75		25.4	(10.0)	39.4	(15.5)	50.8	(20.0)
L 60		33.0	(13.0)	44.5	(17.5)	53.3	(21.0)
L 45		38.1	(15.0)	48.3	(19.0)	55.9	(22.0)
L 30		43.2	(17.0)	52.1	(20.5)	61.5	(24.2)
L 15		46.2	(18.2)	55.9	(22.0)	64.0	(25.2)
0		50.8	(20.0)	58.4	(23.0)	68.6	(27.0)
R 15		54.6	(21.5)	62.2	(24.5)	71.6	(28.2)
R 30		57.2	(22.5)	65.3	(25.7)	73.7	(29.0)
R 45		58.9	(23.2)	69.9	(27.5)	75.4	(29.7)
R 60		62.2	(24.5)	70.4	(27.7)	77.5	(30.5)
R 75		64.0	(25.2)	72.4	(28.5)	76.7	(30.2)
R 90		65.3	(25.7)	72.9	(28.7)	78.7	(31.0)
R 105		66.0	(26.0)	73.7	(29.0)	78.7	(31.0)
R 120		41.1	(16.2)	66.5	(26.2)	74.9	(29.5)
R 135		32.3	(12.7)	49.5	(19.5)	69.9	(27.5)
R 150		27.9	(11.0)	41.1	(16.2)	59.7	(23.5)
R 165		26.7	(10.5)	39.4	(15.5)	55.9	(22.0)
180		24.1	(9.5)	38.1	(15.0)	50.8	(20.0)

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

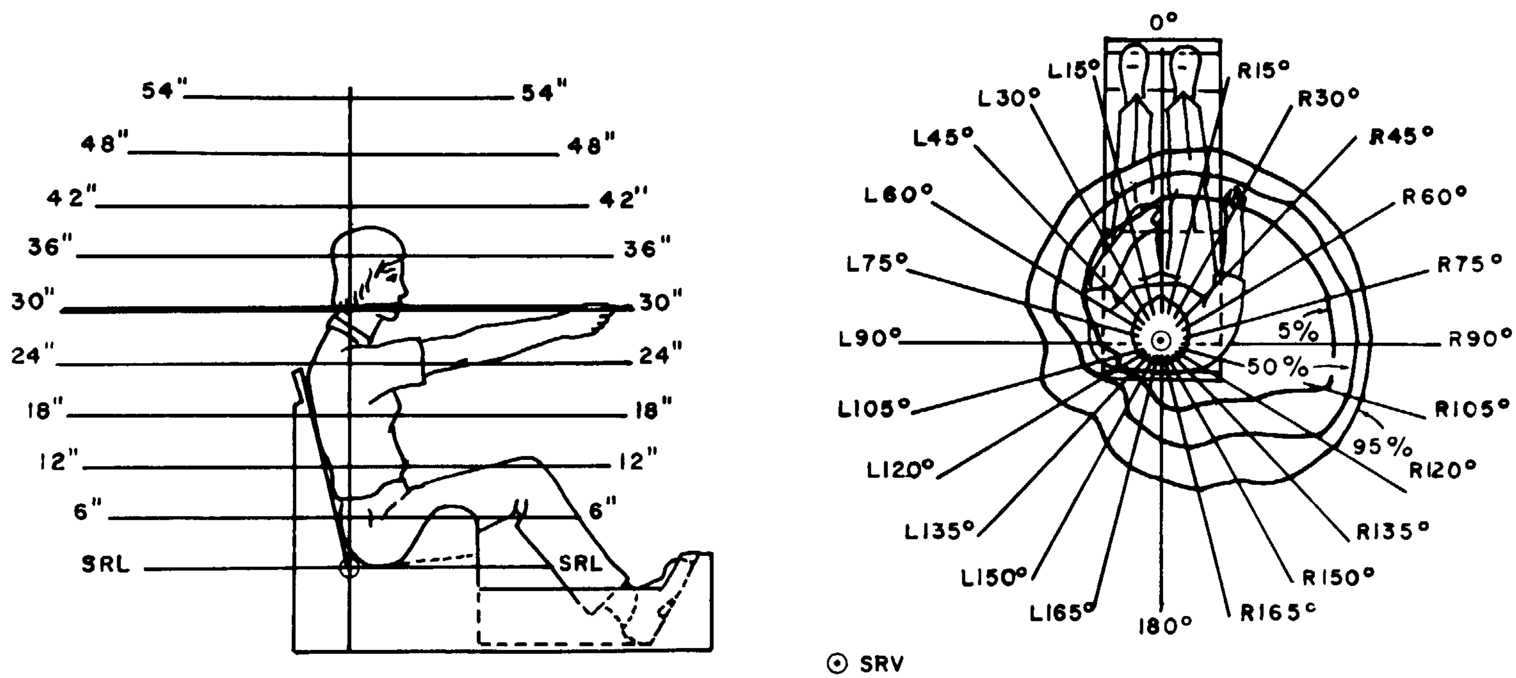


Figure 19. Women's grasping reach to a horizontal plane 30 inches above the seat reference point.

TABLE 18

WOMEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE
91.4 CENTIMETERS (36 in.) ABOVE THE SEAT REFERENCE POINT.
HORIZONTAL DISTANCE FROM THE SRV.*
See Figure 20

Angle to Left or Right	Minimum	Percentiles 5		50		95	
L 165		22.9	(9.0)	33.0	(13.0)	49.5	(19.5)
L 150		20.3	(8.0)	29.2	(11.5)	45.0	(17.7)
L 135		18.3	(7.2)	25.9	(10.2)	40.6	(16.0)
L 120		18.3	(7.2)	25.4	(10.0)	39.4	(15.5)
L 105		18.3	(7.2)	26.7	(10.5)	38.6	(15.2)
L 90		19.6	(7.7)	29.2	(11.5)	40.6	(16.0)
L 75		20.8	(8.2)	33.0	(13.0)	43.7	(17.2)
L 60		25.4	(10.0)	36.1	(14.2)	45.7	(18.0)
L 45		29.2	(11.5)	39.4	(15.5)	49.5	(19.5)
L 30		33.5	(13.2)	43.7	(17.2)	54.6	(21.5)
L 15		36.1	(14.2)	48.3	(19.0)	57.7	(22.7)
0		41.1	(16.2)	52.1	(20.5)	61.0	(24.0)
R 15		44.5	(17.5)	54.6	(21.5)	62.7	(24.7)
R 30		47.0	(18.5)	57.2	(22.5)	66.0	(26.0)
R 45		48.8	(19.2)	61.0	(24.0)	68.6	(27.0)
R 60		52.6	(20.7)	63.5	(25.0)	70.4	(27.7)
R 75		53.3	(21.0)	64.8	(25.5)	71.1	(28.0)
R 90		56.4	(22.2)	66.5	(26.2)	72.9	(28.7)
R 105		53.8	(21.2)	66.5	(26.2)	72.9	(28.7)
R 120		46.2	(18.2)	63.5	(25.0)	70.4	(27.7)
R 135		31.8	(12.5)	48.3	(19.0)	65.3	(25.7)
R 150		25.4	(10.0)	43.7	(17.2)	59.7	(23.5)
R 165		25.9	(10.2)	40.6	(16.0)	55.9	(22.0)
180		24.1	(9.5)	38.6	(15.2)	53.8	(21.2)

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

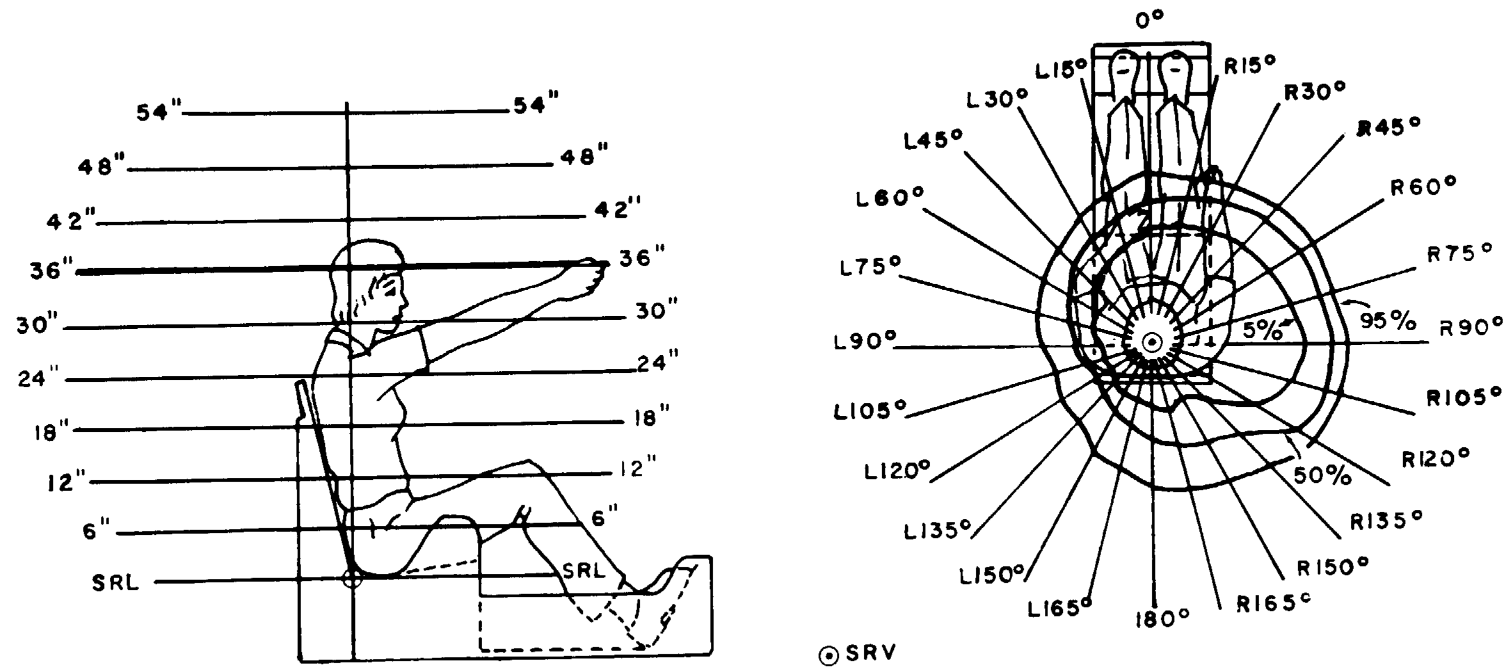


Figure 20. Women's grasping reach to a horizontal plane 36 inches above the seat reference point.

TABLE 19

WOMEN'S RIGHT HAND GRASPING REACH TO A HORIZONTAL PLANE 106.7 CENTIMETERS (42 in.) ABOVE THE SEAT REFERENCE POINT. HORIZONTAL DISTANCE FROM THE SRV.*

See Figure 21

Angle to Left or Right	Minimum	Percentiles					
		5		50		95	
L 165		12.7	(5.0)	25.9	(10.2)	43.2	(17.0)
L 150		10.7	(4.2)	22.9	(9.0)	38.1	(15.0)
L 135		9.4	(3.7)	21.6	(8.5)	34.8	(13.7)
L 120		8.9	(3.5)	20.3	(8.0)	33.0	(13.0)
L 105		8.1	(3.2)	20.3	(8.0)	31.8	(12.5)
L 90		8.9	(3.5)	20.3	(8.0)	33.0	(13.0)
L 75		9.4	(3.7)	22.1	(8.7)	36.8	(14.5)
L 60		10.2	(4.0)	24.1	(9.5)	41.1	(16.2)
L 45		11.9	(4.7)	26.7	(10.5)	40.6	(16.0)
L 30		14.0	(5.5)	29.2	(11.5)	43.2	(17.0)
L 15		16.5	(6.5)	31.8	(12.5)	45.0	(17.7)
0		19.1	(7.5)	35.6	(14.0)	47.0	(18.5)
R 15		22.9	(9.0)	40.6	(16.0)	48.3	(19.0)
R 30		25.4	(10.0)	43.2	(17.0)	52.1	(20.5)
R 45		28.4	(11.2)	44.5	(17.5)	55.9	(22.0)
R 60		30.5	(12.0)	48.3	(19.0)	57.2	(22.5)
R 75		33.0	(13.0)	50.8	(20.0)	59.7	(23.5)
R 90		35.6	(14.0)	50.8	(20.0)	61.0	(24.0)
R 105		35.6	(14.0)	52.1	(20.5)	61.0	(24.0)
R 120		30.5	(12.0)	47.0	(18.5)	59.7	(23.5)
R 135		23.4	(9.2)	39.4	(15.5)	53.8	(21.2)
R 150		19.1	(7.5)	35.6	(14.0)	50.0	(19.7)
R 165		16.5	(6.5)	31.0	(12.2)	48.3	(19.0)
180		14.0	(5.5)	27.9	(11.0)	47.5	(18.7)

*Data given in centimeters with inches in parentheses.

The original data were measured to the nearest ¼ inch and are reported here rounded down to the nearest tenth of an inch.

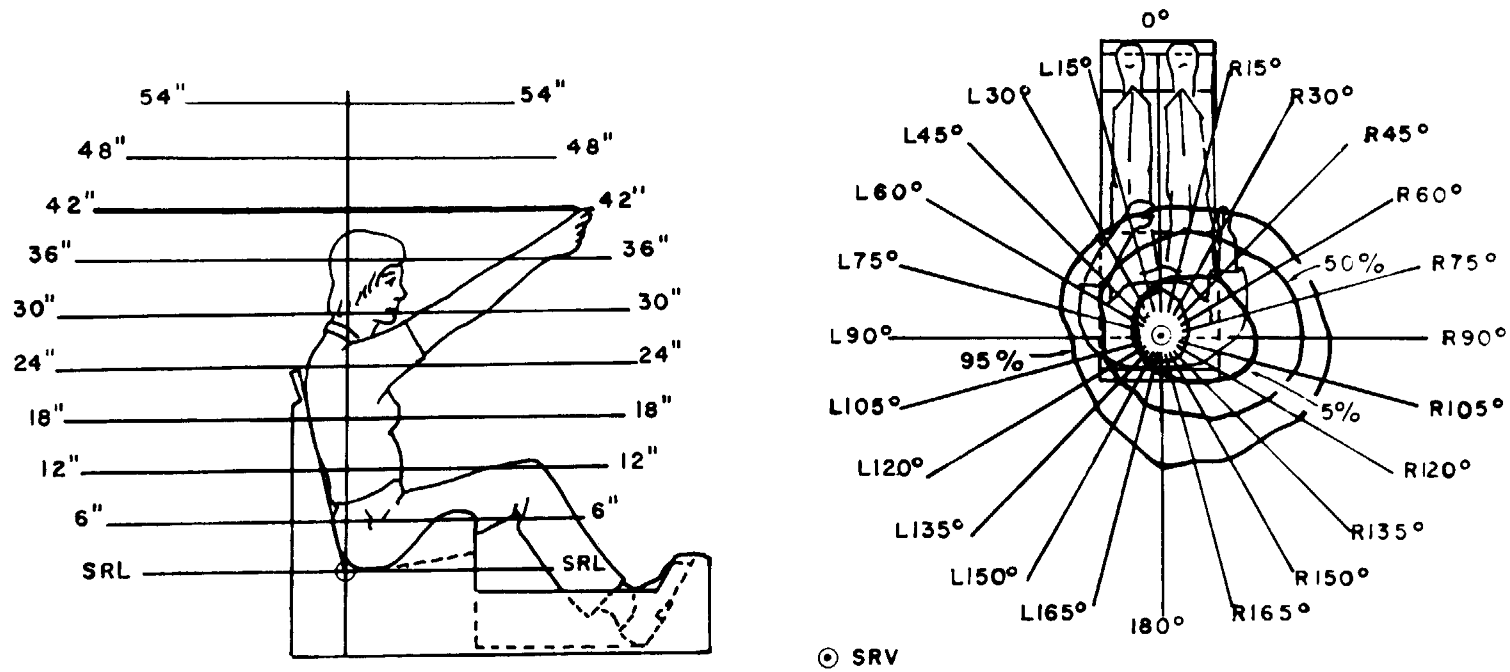


Figure 21. Women's grasping reach to a horizontal plane 42 inches above the seat reference point.

When backrest angles are changed, however, there will be corresponding changes in the functional reaches attainable--assuming other factors remain constant. As the angle of the backrest increases from 103^{o} the shoulders will move rearward, and forward reach distances will be correspondingly reduced; as the backrest assumes a more vertical position, forward reaches will be increased. Both Ely, Thomson and Orlansky (1963) and Bullock (1974) have dealt with the question of changes in reach as a function of changes in backrest angle. Data from the first of these reports indicate that a change in backrest angle from 103^{o} to the vertical (or 90^{o}) results in an increase in directly forward functional reach of about 5 inches (12.7 cm.), or approximately 0.4 inches (1.0 cm.) for each one degree of backrest change. This holds for the area at shoulder height to about 11 inches (27.9 cm.) below this level. This study did not report data for reaches other than straight ahead.

The Bullock study did investigate changes in other angular reaches as a function of changes in backrest angle. Here, it was reported that at a level of 14 inches (35.6 cm.) above the SRP, reaches to the side, or 90^{o} from the midline, were affected least. Differences in reach with backrest change were maximal in the area around 15^{o} from the right of the midline, thereafter decreasing to both the right and left. Changes with a decrease in backrest angle (towards the vertical) were not determined by Bullock, but extrapolation from the above data indicates that, with a vertical backrest, maximal functional forward reaches would be increased above those taken at 103^{o} by about 5.0 inches (12.7 cm.) in reaches made directly to the front, a value that agrees with that of Ely et al. Combining the results of the two studies, we show in Table 20, the increments or decrements, in functional arm reaches that would be expected to result from each one degree of change in backrest angle from the 103^{o} conditions under which the date in Tables 2-19 were obtained. As an example, a change in backrest from 103^{o} to 90^{o} (vertical), would increase 45^{o} angular reach by 13 x 0.37 inches or 4.8 inches (12.2 cm.). It should be noted that these correction factors are expected to be reasonably accurate except for reaches to the highest levels, where the increments will become smaller, with the least change for reach directly overhead.

When shoulders are not kept in contact with the backrest, differences are difficult to quantify because of the great variability in arm reaches afforded by free body movement and by the variability of restrictions caused by different clothing and equipment assemblies. Basic functional reach data are those that are taken under conditions of torso restraints, as in the present Tables 2-19. Here, with the use of the factors in Table 20, corrections may be made to convert the data to vertical backrest conditions--which is the equivalent of defining the arm reach from a vertical plane in back of the shoulder, a useful concept. For example, adding approximately 5 inches (12.7 cm.) to any 0^{o} degree arm reach in Tables 2-19 will give a back-of-the-shoulder-to-finger-grasp reach dimension.

In any event, the practical problems suggested by such differences in backrest angle and body movement clearly indicate the need for further, definitive studies to more accurately determine the best means of transforming existing data in such a way that they will have applicability under differing kinds of conditions.

Zero-G Conditions - Unrestrained or Partially Restrained Body Movement

Another consideration in utilizing the present arm reach data relates to the changes in working conditions in a zero-g environment, where we are normally dealing with the operator in a neutral body position. Here the body may be either totally unrestrained, or partially restrained--in the latter case probably by means of a foot restraint system.

When the body is totally unrestrained, or "free-floating", problems of design layout relative to functional reach would appear to be minimal. With no restraints on body movement, anyone, regardless of body size or related functional reach, should be able to reach to virtually any physically accessible location in or around the workspace with a minimum of difficulty.

With the body restrained or anchored at the feet, zero-g experience in Skylab has led to the observation that for body size in general and arm reach in particular "...the (design) limitations of work stations to 38 inches (96.5 cm.) width...and the use of foot restraints that can be positioned to any height will provide for all possible sizes of 5th to 95th percentile populations" (Thompson, 1975). It is quite true that the ability to position the feet of the operator at any of a variety of positions for body restraint in a zero-g environment lends a dimension of adjustability to the workspace that is not normally found under terrestrial conditions. As a consequence, the much greater flexibility that is afforded for body positioning makes the layout of workspaces and controls on the basis of functional arm reaches considerably easier under zero-g conditions. Deficiencies in arm reach resulting from even markedly smaller body size can be compensated for by the simple expedient of moving the foot restraint position up or down, in or out.

In addition, as a result of zero-g experience in Skylab, it has been stated that the neutral body posture at console stations enables a crewman to "reach approximately 0.4 meter (15.7 inches) beyond his normal seated reach" (Johnson, 1975). Granted that this is an approximation, and that this value would not necessarily apply equally to all reach positions within a workspace, it nevertheless gives a clear indication of the very substantial increases in functional reach that can be expected as part of the normal zero-g working conditions. Adding 15.7 inches (39.9 cm.), or even somewhat less to allow for a "safety factor", to the reach dimensions in Tables 2-19, will greatly simplify the task of providing workspace and control accessibility in Space Shuttle-Spacelab, especially in conjunction with the greatly expanded reach capability afforded by body repositioning through adjustable foot restraint positions.

For these reasons, it would seem that workspace layout and control locations for weightlessness operations should present relatively few problems to the designer. Nevertheless, there may be occasions in which it is necessary to estimate certain reach dimensions with the body in a fixed position. Here the data in Tables 2-19 may again be used. The first correction, as before, should be to change the data from a 103^{o} backrest to a vertical one; reach dimensions can then be assumed to start, functionally, from the back of the shoulder (instead of from the seat reference vertical - SRV). Specific examples are as follows: From Table 20 the appropriate increments can be added to accomplish this purpose, i.e., 5.2 inches (13.2 cm.) to the tabular data for direct forward reach (13^{o} x 0.40); 6.5 inches (16.5 cm.) at 15^{o} ; 5.8 inches (14.7 cm.) at 30^{o}; 4.8 inches (12.2 cm.) at 45^{o} ; 3.3 inches (8.4 cm.) at 60^{o}; 1.8 inches (4.6 cm.) at 75^{o}; and 1.3 inches (3.3 cm.) at 90^{o}. Thus, if a fixed position of the shoulder is assumed, functional reaches can be estimated on the above basis.

Shoulder position will, of course, be dependent in large part upon the locations of the various foot rest surfaces, and the "stature" of the individual in the neutral body position, to which must be added perhaps one to one and one half inches for the shoe restraint suction-cup system.

Conversion Techniques for Different Populations

The functional arm reach measurements presented in Tables 2-19 were taken on healthy, young, adult, U.S. males and females selected to be anthropometrically representative of U.S. Air Force populations. As such they may be assumed to have certain similarities, and some differences, with the intended Space Shuttle-Spacelab populations. Air Force flying personnel and spaceflight groups may be assumed, physically and in terms of body size, to have much in common. First of all they must both be healthy and in good physical condition. Here the requirements for spaceflight crews will, if anything, be more rigid than those for the military generally. In terms of age, the space crews may be more mature, but are not likely to be elderly. They will both be somewhat above average socio-economically and educationally, with the space crews probably markedly higher in the latter category.

All these characteristics tend to be associated positively with larger body size. Spaceflight crews therefore, would be expected on this basis to be at least as large, or possibly larger, than U.S. Air Force flying personnel. Sex differences in body size are also important since both men and women will be represented in the project, but reach data are available separately on both sexes.

The major population differences that will need to be taken into account are those related to nationality and secular change. Ethnic or national differences in body size will be important since not only U.S. personnel will be manning the Spacelab, but probably some Europeans, and perhaps Asiatics, as well. Secondly, since Space Shuttle-Spacelab operations are planned through 1980-1990, and since we know that there is some apparently continuing increase in body size over time, we can anticipate, all other things being equal, a slightly larger spacecraft population in the future.

TABLE 20

APPROXIMATE CHANGES IN ARM REACHES IN TABLES 2-19
AS A FUNCTION OF VARIATION IN SEAT BACKREST ANGLE*

Direction of arm reach (from 0° or "straight ahead," to 90° to the right)	Approximate changes in reach for each single degree of change in backrest angle (reach increases as backrest angle moves to vertical, and vice versa)
0°	$\pm$ 1.02 cm. ($\pm$ 0.40 in.)
15°	$\pm$ 1.27 cm. ($\pm$ 0.50 in.)
30°	$\pm$ 1.14 cm. ($\pm$ 0.45 in.)
45°	$\pm$ 0.94 cm. ($\pm$ 0.37 in.)
60°	$\pm$ 0.66 cm. ($\pm$ 0.26 in.)
75°	$\pm$ 0.36 cm. ($\pm$ 0.14 in.)
90°	$\pm$ 0.25 cm. ($\pm$ 0.10 in.)

*Derived from Ely et al. (1963) and Bullock (1974).

With regard to the latter consideration, it should be pointed out that both the male and female populations for which the arm reach data are presented are above average in body size. They are, in fact, very close to the projected 1980 statures for males and females, and functional reach tends to be highly correlated with stature. Specifically, mean stature of present arm reach males is 69.6 inches (176.8 cm.); projected 1980 mean male stature is 69.5 inches (176.5 cm.). Mean stature of arm reach females is 64.1 inches (162.8 cm.); projected 1980 mean female stature is 64.2 inches (163.1 cm.). In other words, the secular increase in body size need not be taken into account in planning for functional arm reaches of Space Shuttle-Spacelab populations through 1980. For projections for 1990, a further stature increase for males of 0.5 inches (1.3 cm.), and 0.4 inches (1.0 cm.) for females might be postulated, though this is an upper, outside, estimate. Due to the apparent slowing of secular "growth" recently noted for the population from which U.S. astronauts come, any such increase over that 10 year period, would likely be less than those values with rather minimal effects on functional arm reach.

Ethnic, or national, differences in body size, and therefore in functional arm reach, on the other hand, can be of considerable importance. In general, Northwest Europeans will be fairly similar in body size to our United States populations, Southern or Eastern Europeans somewhat smaller, and Asiatics, especially Southeastern Asiatics, the smallest of all. Since the major area of concern relative to functional arm reach is almost always that of the smallest person with the shortest reaches, attention should be directed to the smallest persons likely to be utilizing Spacelab work areas. The 5th percentile Asiatic female would appear to be the most likely candidate, although it should be remembered that personnel selection on the basis of body size, could be employed to establish any desired lower limits of body size.

The present female arm reach data in Tables 12-19 are based on a U.S. population, and the 5th percentile values will therefore be somewhat larger than the corresponding 5th percentile reaches of Asiatic females. Unfortunately, anthropometric data on Southeast Asiatic females comparable to that on U.S. females are not available. Such data on males are available, however, and comparisons between South Vietnamese military groups (one of the very smallest world populations in terms of body size) show that in terms of stature and related body measurements, 5th percentile Vietnamese military personnel have values about 90% of those of 5th percentile U.S. Air Force flying personnel. Comparable percentages for anatomic arm lengths is about 93-94%. Presumably, the corresponding relationships between 5th percentile female Vietnamese and 5th percentile U.S. females would not be too different.

While it is true that functional reach dimensions are not determined solely by static body dimensions, there is nevertheless a strong positive correlation between the two types of measurements (Stoudt, 1973), and it is not unreasonable therefore to assume the same kind of percentage relationship relative to 5th percentile functional reaches. If this is done, the use of a 90% factor applied to the 5th percentile female data in Tables 12-19 should provide a conservative estimate of the 5th percentile functional reach of a very small Asiatic female population. This would be the lower limit of functional reaches to be accommodated.

Leg Reach Data and Its Applications

As compared to the relatively voluminous data available on functional arm reaches from a variety of studies, leg reach data may be said to be minimal. There is, in fact, not one study dealing with leg reaches that has been carried out in the detailed manner of any of the more comprehensive arm reach studies. The single best available study is that of Laubach and Alexander (n.d.), as yet unpublished. Measurements were taken of knee heights and heel point positions in both favored or "comfortable", and maximally extended leg positions.

However, neither these nor any other leg reach data would seem to have any special applicability to Spacelab conditions. Neither the zero-g condition, nor the neutral body position, unrestrained or partially restrained, would appear to be particularly appropriate for the use of foot controls, especially if some type of foot or shoe restraint system is employed. It is true that the Space Shuttle pilot and co-pilot locations might require foot controls similar to those in present day aircraft, but here existing design specifications should be adequate since (presumably) the personnel would be similar in body size and leg reach to U.S. Air Force flying personnel. It is only in Spacelab, with its potentially wide range of body size variability, e.g., 95th percentile U.S. male to 5th percentile Asiatic female, that design problem of leg reach accommodation might have been expected to occur.

It is not, therefore, considered advisable to make recommendations relative to functional leg reaches in Skylab for the following reasons: (1) first and most importantly, the lack of any adequate body of anthropometric data defining functional leg reaches for male and female populations; (2) the difficulties of using foot controls in a zero-g environment, especially with a foot restraint, shoe suction-cup system; and (3) finally, the lack of any apparent clear-cut need for foot controls in the Spacelab working environment.

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ADDITIONAL DATA SOURCES

The following documents are not readily available because of limited distribution (unpublished or preliminary data). However, copies/information may be obtained by contacting the author/source.

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